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**Applicability of Transmissometers to Opacity  
Measurement of Emissions, Oil-Fired  
Power and Portland Cement Plants**

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Research and Development



# Applicability of Transmissometers to Opacity Measurement of Emissions

## Oil-Fired Power and Portland Cement Plants

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| 16. ABSTRACT<br>In-stack transmissometers were evaluated for their capability to monitor the opacity of smoke-stack plumes emitted by portland cement plants and oil-fired power plants. Tests were conducted to determine their performance in four areas: the adequacy of the U.S. Environmental Protection Agency-promulgated transmissometer design and performance specifications for the sources, the correlation between the opacity of the emissions measured in the plume and in the stack of the sources, as well as the existence of a functional relationship between the transmissometer-measured opacity and mass concentration of the particulate emission.<br><br>The results indicated that the promulgated design and performance specifications for transmissometers are adequate for both sources except for the spectral response design specification; the allowable peak spectral response range may be too large for oil-fired power plants. For opacity monitoring of submicrometer particulate emissions like those from oil-fired power plants, the allowable peak spectral response range of the transmissometer should be reduced. In addition, the in-stack transmissometer-measured opacity for oil-fired power plants was generally lower than the plume opacity, indicating that much of the particulates in the plumes were forming in the atmosphere out of the stack. Correlations were observed between the transmissometer-measured opacity and mass concentration of the particulate emissions from both sources. |                                                           |                                              |
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APPLICABILITY OF TRANSMISSOMETERS TO  
OPACITY MEASUREMENT OF EMISSIONS  
Oil-Fired Power and Portland Cement Plants

by

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## ABSTRACT

In-stack transmissometers were evaluated for their capability to monitor the opacity of smoke-stack plumes emitted by certain sources. In-stack transmissometers were installed on three portland cement plants and three oil-fired power plants. Tests were conducted to determine their performance in four areas: the adequacy of the U.S. Environmental Protection Agency-promulgated transmissometer design and performance specifications for the sources, the correlation between the opacity of the emissions measured in the plumes and in the stacks of the sources, as well as the existence of a functional relationship between the transmissometer-measured opacity and mass concentration of the particulate emission.

For portland cement plants, the results indicated that the promulgated design and performance specifications for transmissometers are adequate. The in-stack transmissometer measured opacity was found to be representative of the plume opacity and to correlate to the mass concentration of the particulate emissions.

For oil-fired power plants, the results indicated that the promulgated design and performance specifications for transmissometers are adequate except for the spectral response design specification. For opacity monitoring of submicrometer particulate emissions such as those from oil-fired power plants, the allowable peak spectral response range of the transmissometer should be reduced. In addition, the in-stack transmissometer-measured opacity for oil-fired power plants was generally lower than the plume opacity, indicating that much of the particulates in the plumes were forming in the atmosphere out of the stack. Correlation was observed between the transmissometer-measured opacity and mass concentration of the oil-fired power plant particulate emissions.

## CONTENTS

|                                                   |      |
|---------------------------------------------------|------|
| Abstract . . . . .                                | iii  |
| Figures . . . . .                                 | vi   |
| Tables . . . . .                                  | vii  |
| Acknowledgments . . . . .                         | viii |
| 1. Introduction . . . . .                         | 1    |
| 2. Conclusions . . . . .                          | 3    |
| 3. Design Specifications . . . . .                | 5    |
| Spectral specifications . . . . .                 | 6    |
| Collimation specifications . . . . .              | 7    |
| 4. Performance Specifications . . . . .           | 11   |
| In-stack and plume opacity . . . . .              | 11   |
| In-stack opacity and mass concentration . . . . . | 12   |
| 5. Measurement Methods . . . . .                  | 14   |
| Opacity measurement . . . . .                     | 14   |
| Particulate mass measurement . . . . .            | 15   |
| Particle size measurement . . . . .               | 15   |
| Multiwavelength opacity measurement . . . . .     | 18   |
| 6. Cement Plant Tests . . . . .                   | 19   |
| Test sites . . . . .                              | 19   |
| Results and discussion . . . . .                  | 23   |
| 7. Oil-Fired Power Plant Tests . . . . .          | 33   |
| Test sites . . . . .                              | 33   |
| Results and discussion . . . . .                  | 34   |
| References . . . . .                              | 47   |

## FIGURES

| <u>Number</u>                                                                                                                                                               | <u>Page</u> |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| 1 Measured opacities as a function of true (theoretical) opacities for a transmissometer with a 20° angle of view and aerosols with different mean particle sizes . . . . . | 9           |
| 2 Measured opacities as a function of true (theoretical) opacities for transmissometers with 2° and 20° angles of view and specified aerosol . . . . .                      | 10          |
| 3 Photograph of mobile lidar system . . . . .                                                                                                                               | 16          |
| 4 Schematic of cement plant test site I . . . . .                                                                                                                           | 20          |
| 5 Schematic of cement plant test site II . . . . .                                                                                                                          | 21          |
| 6 Schematic of cement plant test site III . . . . .                                                                                                                         | 22          |
| 7 Particle size distributions of portland cement plants . . . . .                                                                                                           | 28          |
| 8 In-stack opacity of emissions from portland cement plants as a function of the mass concentration of the particulates at standard conditions and dry gas . . . . .        | 31          |
| 9 In-stack opacity of emissions from portland cement plants as a function of the mass concentration of the particulates at actual conditions . . . . .                      | 32          |
| 10 Schematic of oil-fired power plant test site I . . . . .                                                                                                                 | 35          |
| 11 Schematic of oil-fired power plant test site II . . . . .                                                                                                                | 36          |
| 12 Schematic of oil-fired power plant test site III . . . . .                                                                                                               | 37          |
| 13 Particle size distributions of oil-fired power plants . . . . .                                                                                                          | 41          |
| 14 Particle size distribution of oil-fired power plant III . . . . .                                                                                                        | 42          |
| 15 In-stack opacity of emissions from oil-fired power plants as a function of the mass concentration of the particulates at standard conditions and dry gas . . . . .       | 45          |

## FIGURES (Continued)

| <u>Number</u> |                                                                                                                                                      | <u>Page</u> |
|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| 16            | In-stack opacity of emissions from oil-fired power plants as a function of the mass concentration of the particulates at actual conditions . . . . . | 46          |

## TABLES

|   |                                                               |    |
|---|---------------------------------------------------------------|----|
| 1 | Specifications for Transmissometer Opacity Monitors . . . . . | 2  |
| 2 | Mobile Lidar System Characteristic . . . . .                  | 17 |
| 3 | Cement Plant Opacity Measurements . . . . .                   | 24 |
| 4 | Cement Plant II Anderson Impactor Data . . . . .              | 26 |
| 5 | Cement Plant III Anderson Impactor Data . . . . .             | 26 |
| 6 | Cement Plant IV Pilot Impactor Data . . . . .                 | 27 |
| 7 | Oil-Fired Power Plant Opacity Measurements . . . . .          | 38 |
| 8 | Oil-Fired Power Plant Pilot Impactor Data . . . . .           | 40 |

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## SECTION 1

### INTRODUCTION

In-stack transmissometer design and performance specifications for monitoring the opacity of visible emissions were promulgated by the U.S. Environmental Protection Agency (EPA) on October 6, 1975 (1). Although the specifications (see Table 1) are intended to be generally applicable to monitoring the opacity of emissions from a wide range of industries, the transmissometers should still be evaluated for each industry. The evaluation should determine four performance areas:

- the adequacy of the transmissometer design specifications for the source,
- the adequacy of the transmissometer performance specifications for the source,
- the correlation between the opacity of the emissions measured in the plume and in the stack of the source, and
- the existence of a functional relationship between the transmissometer-measured opacity and mass concentration of the particulate emissions.

The most extensive studies concerning the application of in-stack transmissometers to opacity measurements are reported for coal-fired power plants. Data are reported on the effects of transmissometer spectral response and collimation characteristics on the measurement of opacity at a coal-fired power plant (2), on correlation between in-stack and plume opacities at coal-fired power plants (2,3,4), on correlations between opacity and mass concentration at coal-fired power plants (5,6), and on the performance stability of a transmissometer at a coal-fired power plant (7). These studies have demonstrated that the EPA-promulgated specification for transmissometers are adequate for the conventional coal-fired power plant with electrostatic precipitator

TABLE 1. SPECIFICATIONS FOR TRANSMISSOMETER  
OPACITY MONITORS

| DESIGN SPECIFICATIONS      |                              |                                                       |
|----------------------------|------------------------------|-------------------------------------------------------|
| Parameter                  | Specification                |                                                       |
| A                          | Spectral response            | Peak: within 500 to 600 nm                            |
|                            |                              | Mean: within 500 to 600 nm                            |
|                            |                              | Limit: less than 10% of peak<br>outside 400 to 700 nm |
| B                          | Angle of view                | 5° maximum (total angle)                              |
| C                          | Angle of projection          | 5° maximum (total angle)                              |
| PERFORMANCE SPECIFICATIONS |                              |                                                       |
| Parameter                  | Specification                |                                                       |
| A                          | Calibration error            | ≤ 3% opacity                                          |
| B                          | Zero drift (24 hours)        | ≤ 2% opacity                                          |
| C                          | Calibration drift (24 hours) | ≤ 2% opacity                                          |
| D                          | Response time                | 10 sec (maximum)                                      |
| E                          | Operational test period      | 168 hr                                                |

particulate control equipment. Additional studies have reported on the application of transmissometers to the measurement of opacity at a steel mill (basic oxygen furnace), at a cement plant, and at a sulfuric acid plant (8), at a petroleum plant (catalytic cracker regenerator), an asphalt concrete plant, a sludge incinerator, a secondary brass/lead smelter, and an oil-fired power plant (9).

In this report, the specifications required for transmissometer opacity monitors by EPA are reviewed. Also, the field tests are described that were conducted at several portland cement and oil-fired power plants to evaluate the adequacy of the specifications for monitoring the opacity of emissions from these two sources.

## SECTION 2

### CONCLUSIONS

The data for portland cement plants showed that the promulgated transmissometer opacity monitor design specifications for spectral response and collimation are both adequate. The peak and mean spectral response specification limits of 500 and 600 nm could be broadened to 400 and 700 nm without affecting the opacity measurement. Any broader expansion into the ultraviolet and infrared spectral regions should be avoided, primarily because of water vapor and other gas absorption bands. For similar reasons, the overall spectral response limits of 400 and 700 nm should not be changed.

The performance (drift stability) specifications for the transmissometers were found adequate for cement plants. Consequently, no need for changes were indicated.

The in-stack opacity measurements when compared to out-of-stack plume opacity measurements at cement plants indicated that the in-stack transmissometer will monitor the plume opacity when installed and spanned according to the promulgated specifications. However, there was a notable exception. During cold weather the opacity of the plume can become higher than the in-stack opacity due to condensation. When this occurred, the condensation and higher opacities were not observed in the stack.

Good functional relationships were observed between the opacities and particulate mass concentrations of the portland cement plant emissions. Light attenuation coefficient versus mass concentration curves for four plants were linear with regression line slopes within  $\pm 18$  percent when the mass measurements were reduced to standard conditions and dry gas. When the mass measurements were for actual conditions, the slopes were within  $\pm 33$  percent.

The data for oil-fired power plants showed a potential problem with the promulgated design specifications for spectral response when applied to this

source. The opacities of the particulate emissions from these plants were observed to be very dependent upon the wavelength of the light within the visible part of the spectrum. The 500 to 600 nm wavelength range allowed in the peak spectral response of transmissometers by the EPA specifications can result in a variation of about  $\pm 25$  percent ( $\pm 5$  percent opacity) relative to 20 percent opacity green light (550 nm) measurement. This potential 10 percent opacity difference between transmissometers with 500 and 600 nm peak spectral responses is excessive and should be reduced. The potential error can be cut in half by reducing the allowable peak response range of 100 nm to 50 nm. In reducing the peak response range specification to 50 nm, the present range should be reduced by subtracting 25 nm from both ends to allow a narrower range from 525 to 575 nm wavelength. The new range would encompass and remain symmetrical with the peak (photopic) response of the human eye (550 nm). Such a reduction is recommended when transmissometers are used to measure the opacity of emissions with particulates as small as those emitted by oil-fired power plant sources.

The performance (drift stability) specifications for the transmissometers were found adequate for oil-fired power plant in-stack opacity monitoring. No need for change was indicated.

The data did show a problem when the in-stack transmissometer was used to monitor the opacity of plumes emitted by an oil-fired power plant. The in-stack opacity measurements were generally lower than the out-of-stack plume opacity measurements. The higher plume opacities were attributed to condensing sulfuric acid ( $\text{H}_2\text{SO}_4$ ) as the gases exited from the stacks. The differences are related to such variables as the sulfur content of the fuel, boiler excess air, and probably atmospheric variables such as ambient temperature, humidity, etc., which would preclude a simple correction factor.

Functional relationships were also observed between the opacities and particulate mass concentration of the oil-fired power plant emissions. Two distinct light attenuation versus mass concentration curves were apparent. One curve was for plants operating at excess oxygen firing levels of 1.5 to 3.0 percent. The other curve was for a plant specially designed to normally operate at a low excess oxygen level of 0.2 percent. Both curves were linear with slopes that differed by factors of 3.0 and 2.2 when the mass measurements were for standard conditions (dry gas) and actual conditions, respectively.

### SECTION 3

#### DESIGN SPECIFICATIONS

Design specifications to define opacity measurement accuracy are unique to the opacity monitor. For gas monitors, accuracy is specified relative to measurements obtained by a prescribed reference (compliance) method. For opacity measurement, however, the compliance method is the trained observer, while the reference opacity measurement method for the trained observer certification is a transmissometer. Consequently, it is necessary to establish design specifications based on those optical characteristics of the transmissometer that affect and define the opacity measurement obtained by the transmissometer.

Two design requirements are specified for transmissometers used to monitor opacity (1):

- The peak spectral response of the transmissometer shall be between 500 and 600 nm wavelength and the responses at 400 and 700 nm wavelength shall be less than 10 percent of the peak response.
- The angle of projection of the light beam and the angle of view of the receiver shall both be less than 5° total angle.

Spectral response and collimation angles can have very significant effects on the opacity measurement performance of transmissometers. They must be standardized to obtain valid opacity measurement. In general, the effects of different spectral responses and collimation angles on opacity measurements are related to the size of the particulates in the effluent: the smaller the particle the greater the wavelength effect, the larger the particles the greater the collimation effect.

## SPECTRAL SPECIFICATIONS

To determine the adequacy of the design specifications for spectral response, the opacity-wavelength characteristic of the emissions near the center (green) of the visible spectrum are first measured. This opacity-wavelength characteristic is then used to calculate the differences between opacity measurements by transmissometers with peak spectral responses at the specification extremes of 500 and 600 nm with respect to a transmissometer operating at 550 nm. The potential error is calculated relative to the opacity measurement that would have been obtained at 550 nm because this is the peak spectral response of the human eye and would be most closely related to the visual effects of the emissions. The potential error is calculated for the promulgated new source opacity standard of the source being examined.

For the calculation, Bouquer's law (often called the Lambert-Beer law) for defining the transmission of light (T) through an aerosol is used. The law may be written as

$$T = \exp. (-N \bar{a} \bar{Q} \ell) \quad (\text{Eq. 1})$$

where N = the number concentration of the particles in the aerosol

$\bar{a}$  = the mean particle area

$\bar{Q}$  = the mean particle extinction coefficient, and

$\ell$  = the length of the light path through the aerosol

If the opacity of the aerosol measured simultaneously at two different wavelengths in the visible spectrum is observed to be different, the mean diameter of the particles can be expected to be less than 1  $\mu\text{m}$ , and the extinction coefficient can be expected to be varying in proportion to  $\lambda^{-n}$  where  $0 < n < 4$  (10). If the plume transmittances are  $T_1$  and  $T_2$  when measured at wavelengths  $\lambda_1$  and  $\lambda_2$ , a value of n is obtained for an intermediate  $\lambda$  from the following relationship:

$$\ln T_2 / \ln T_1 = (\lambda_2 / \lambda_1)^{-n} \quad (\text{Eq. 2})$$

The opacity ( $O_x$ ) at 600 nm and 500 nm relative to the opacity standard ( $O_s$ ) at 550 nm are calculated from the relationship

$$O_x = 1 - (1 - O_s)^R \quad (\text{Eq. 3})$$

with  $R = (.55/.60)^n$  and  $R = (.55/.50)^n$ , respectively.

## COLLIMATION SPECIFICATIONS

Particulate opacity is caused by a reduction in transmitted light due to the scatter and absorption of light by the particles in the emissions. If the correct opacity is to be measured, the transmissometer receiver must not detect the light scattered by the particulates. To exclude the scattered light, the light projection and receiver viewing angles of the transmissometer must be limited to small angles, so that as much collimation is obtained as is practical (7). In practice, complete collimation cannot be obtained; some scattered light will be measured, resulting in an opacity measurement that is lower than the opacity that would be measured by a theoretical, completely collimated transmissometer.

The effect of scattered light measurement on the measurement accuracy of transmissometers has received considerable study (2,11,12). These studies show that the error is generally insignificant for measurements on aerosols with particulate sizes less than  $1/2 \mu\text{m}$  diameter, even when transmissometers with relatively poor collimation are used. For larger particles, however, the error can be significant if transmissometers with poor collimation are used. The error is primarily due to the measurement of light scattered by the particles in the forward direction by diffraction and has been shown to increase with decreasing transmissometer collimation (increasing light projector and receiver viewing angles), increase with increasing particle size, decrease with increasing width of the particle size distribution, and not change significantly with changing composition or refractive index of the particles. In addition, when the measurement pathlength is large compared to the diameter of the beam and receiver aperture, all of the light scattered within the receiver and projector collimation angles will not be measured. As a result, the error will decrease with increasing pathlength. The theoretical calculations by Ensor and Pilat (12) illustrate the need for collimating transmissometers. Their data can be used to show the potential magnitude of the error. Figure 1 depicts the measured opacities that would be obtained with a transmissometer having a  $20^\circ$  receiver angle as a function of the true opacity (the theoretical opacity that would be obtained with perfect collimation) for aerosols with log-normal particle distributions with standard deviations of three and different mean sizes. Figure 2 shows the opacities

that can be expected with transmissometers have  $2^\circ$  and  $20^\circ$  receiver angles of view for an aerosol with a log-normal particle size distribution with a standard deviation of 3 and mean diameter of  $6\text{ }\mu\text{m}$ .

Figures 1 and 2 are for transmissometers with complete collimation (no divergency) of the projected light beam. A transmissometer that used a laser for the light projector would have essentially no divergence of the projected light beam. However, most commercial transmissometers use incandescent lamps and collimating optics. Experimental measurements by Peterson and Tomaides (2) of the effects of the transmissometer light beam projection and receiver viewing angles on measuring the transmittance of a coal-fired power plant emission showed that collimation of the light projection angle was as important as collimation of the view of the light receiver.

The smallest collimation angles that appear feasible before alignment problems and costs become unreasonable are about  $2^\circ$  total angle. The collimation angles of most conventional transmissometers are between  $2^\circ$  and  $3^\circ$ , total angle. Laser transmissometers have been proposed (and one is commercially available) that would have projection angles near  $0^\circ$ ; however, the receiver angle would still have to be several degrees in order to obtain some alignment stability. Long-term alignment may be a problem even then, as very stringent laser alignment must be maintained, particularly for large diameter stacks.

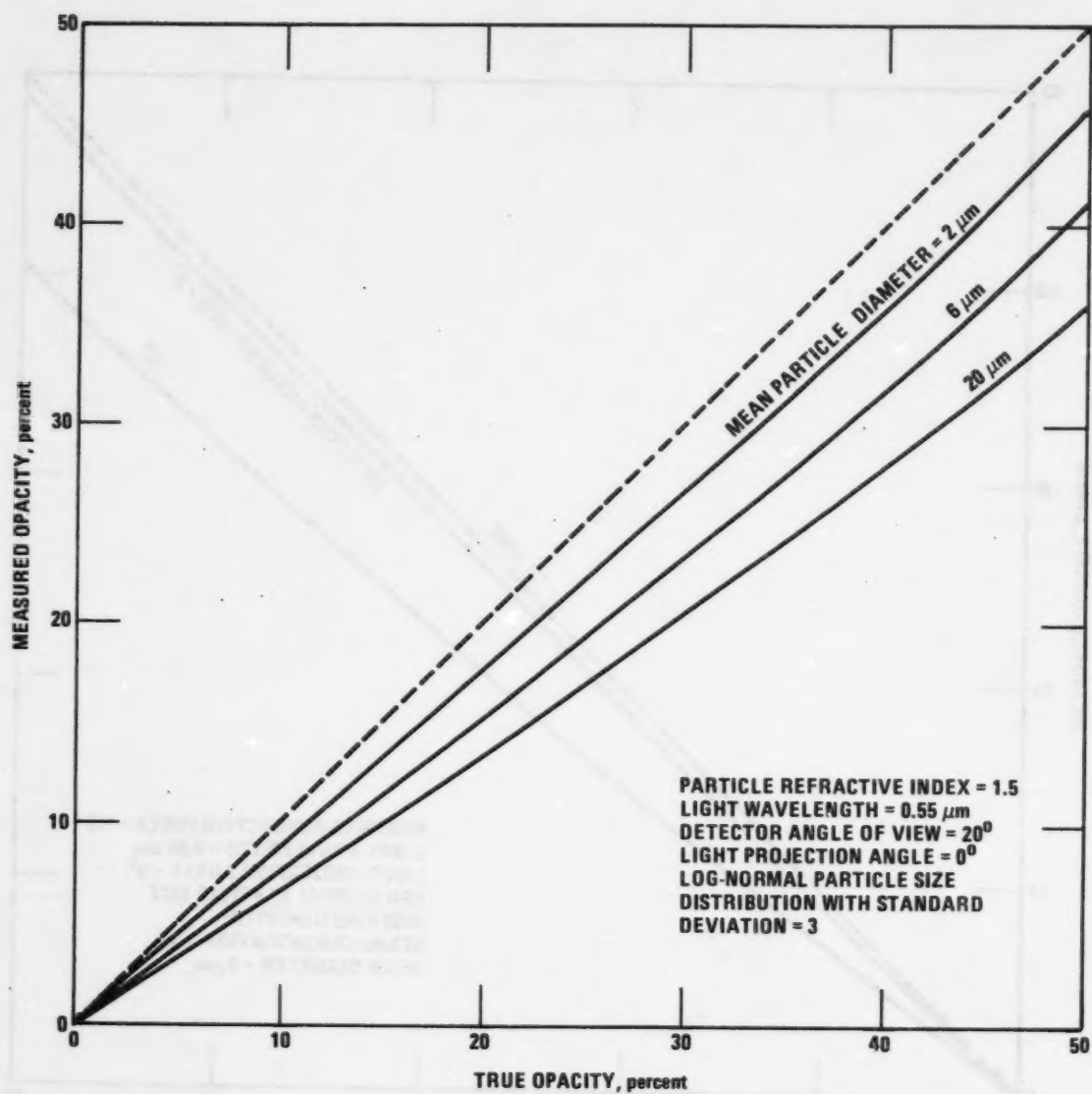


Figure 1. Measured opacities as a function of true (theoretical) opacities for a transmissometer with a 20° angle of view and aerosols with different mean particle sizes.

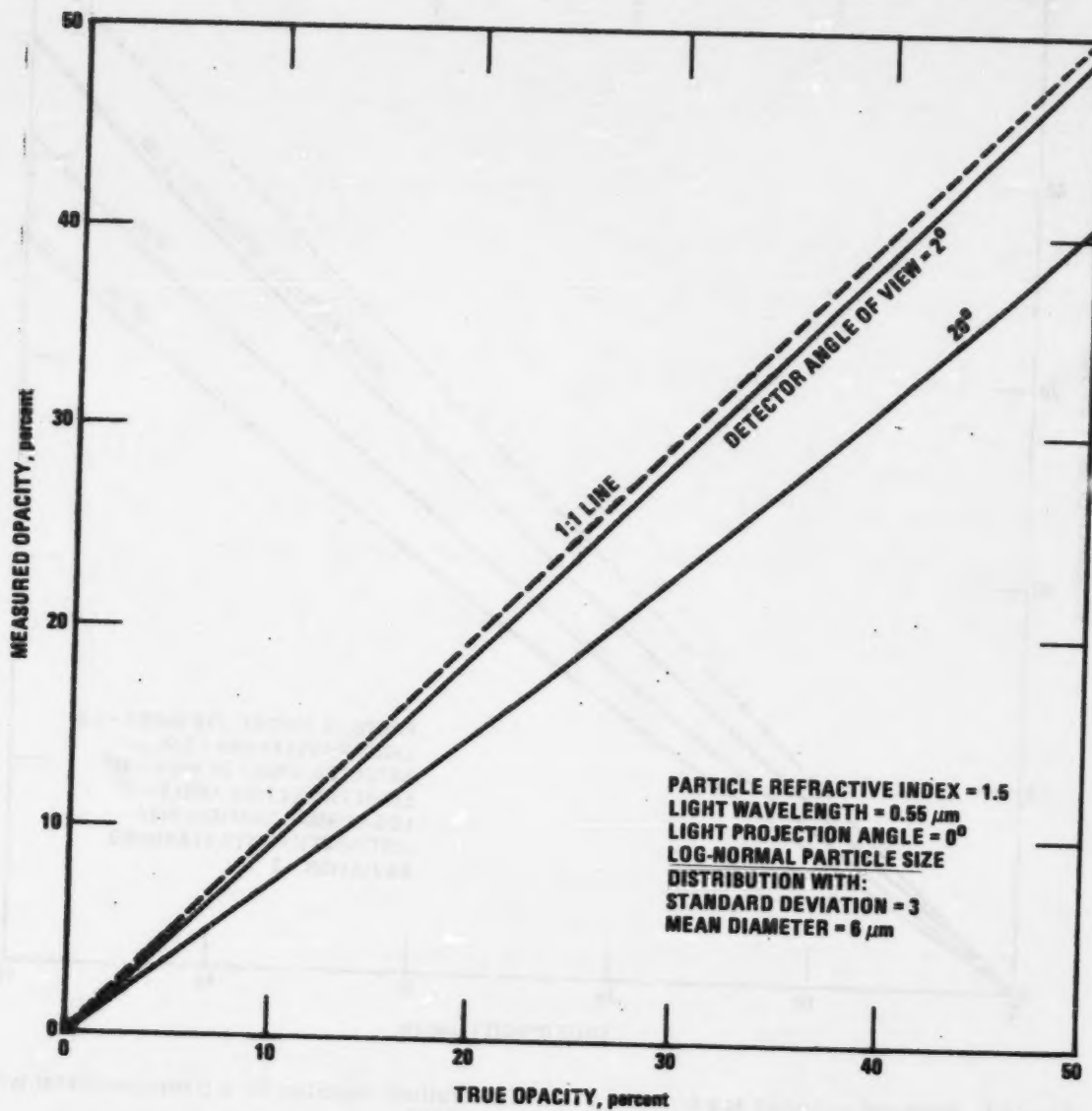


Figure 2. Measured opacities as a function of true (theoretical) opacities for transmissometers with  $2^\circ$  and  $20^\circ$  angles of view and specified aerosol.

## SECTION 4

### PERFORMANCE SPECIFICATIONS

The performance specifications for transmissometers are concerned with calibration error (relative to neutral density calibration filters), response time, and drift stability. These specifications are generally not related to source effects, but are more related to the quality of the specific monitoring systems and to the quality of the specific installations. For example, no transmissometer can have the necessary drift stability if it is improperly installed and becomes misaligned, or if the purge system selected for the installation is not adequate to prevent the transmissometer optics from becoming dirty. Furthermore, a particular monitoring system and installation procedure that provides adequate drift stability at a particular location at one plant may not necessarily provide adequate drift stability at another plant or even at another location at the same plant.

Although the performance specifications are not generally related to source effects, any unusual characteristics of the source are noted that may prevent the transmissometer from monitoring the opacity of the emissions according to the promulgated stability requirements of the performance specifications. In addition, the capability of the in-stack transmissometer to monitor the opacity of the plumes and mass concentration of the particulates emitted by the sources are evaluated. Comparative evaluations of in-stack and plume opacities and particulate concentrations are important for proper interpretation of the transmissometer data.

#### IN-STACK AND PLUME OPACITY

Opacity emission standards apply to the opacities of the plumes emitted by emission sources; consequently, the in-stack and plume opacities must be equivalent, or at least a consistent relationship established, if the in-stack

transmissometer is to be acceptable for monitoring the emission standard. When the characteristics and/or concentration of the particulates in the stack of an emission source are not the same as in the plume, the in-stack and plume opacities will most likely differ. These differences can be due to reactions between particulates and gases, agglomeration of particulates, formation of particulates by condensation, dilution of the effluent, etc. To determine whether the in-stack transmissometer can monitor the plume opacities of a source, concurrent measurements of the in-stack and plume opacities of the source of interest are compared.

#### IN-STACK OPACITY AND MASS CONCENTRATION

The main purpose of opacity monitoring is to determine that the particulate emission control equipment is functioning properly (13). A functional relationship between the opacity of the effluent and mass concentration of particulates in the effluent must exist for changes in the performance of particulate control equipment to be shown by changes in the opacity of the particulate emissions. The simplest way to determine the opacity-mass relationship for an emission is to install a transmissometer in the source to measure opacity, measure the mass concentration of the source by an acceptable gravimetric sampling method, make the measurements at several emission levels and finally plot a curve of opacity versus mass concentration. In practice, the measurements should be made at a location in the stack (or duct) that is acceptable for extracting the particulate samples for gravimetric analyses. The transmissometer is preferably an across-stack (long path) transmissometer that measures the opacity across the entire stack (or duct) and the particulate samples are obtained by traverse sampling along the axis and near the light beam of the transmissometer. With proper precaution to avoid potential problems due to stratification of the particulates, it is likely that valid data can be obtained with portable (short path) transmissometers and point samples. Several emission levels can usually be obtained at a plant by varying the efficiency of the particulate emission control equipment.

The relationship between the opacity and mass concentration of a particulate emission can be defined by the following equation:

$$O = 1 - T = 1 - e^{-\sigma \ell} = 1 - e^{-AC\ell} \quad (\text{Eq. 4})$$

where  $O$  = opacity,

$T$  = light transmission,

$\ell$  = pathlength of opacity measurement,

$\sigma$  = attenuation of light per unit pathlength,

$C$  = mass concentration, and

$A$  = attenuation per unit path length per unit mass concentration.

The attenuation coefficient  $\sigma$  and the attenuation coefficient per unit mass concentration  $A$  are both dependent upon the number concentration, and the physical characteristics of the particles in the emission - size, size distribution, shape, and refractive index.  $A$  (and  $C$ ) is also dependent upon the density of the particles. Equation 4 shows that the opacity-mass concentration relationship of an emission depends on the chemical and physical characteristics of the particulates, as well as on the pathlength of the opacity measurement. Furthermore, the opacity and mass concentration are logarithmically related if the chemical and physical characteristics of the particulates are constant.

For easy comparison of data, the opacity versus mass concentration data from the different plants are all shown for an opacity pathlength normalized to 3 m (10 ft), even though the opacity measurements may have been made at other pathlengths. In addition to the opacity scale, the attenuation coefficient ( $\sigma$ ) scale is shown since it is the optical characteristic of the emission that can be calculated from the opacity measurement that is expected to be proportional to the mass concentration of the emission. The slopes ( $A$ ) of the attenuation coefficient versus mass concentration curves determine the consistency or lack of consistency between the transmissometer optical measurement and mass concentration of the emission sources.

## SECTION 5

### MEASUREMENT METHODS

A number of measurement methods were used to determine the physical characteristics and opacities of the particulate emissions. The methods and procedures used at a particular plant varied and will be noted when describing the tests in Section 6 of the report. A brief description of all the measurement methods will be given here with reference to more detailed descriptions.

#### OPACITY MEASUREMENT

The in-stack opacities were measured with either portable or "permanently" installed Lear Siegler transmissometers. For the "permanent" installations the Model RM4 was used. For the portable measurements either the Model RM41P with the one meter probe or the RM4 equipped with the RM41P one meter probe were used. Transmissometer calibrations were checked with neutral density filters. The locations for the transmissometer measurements were either in the stack or stack breeching and varied between plants. The locations were usually dependent upon the availability of sampling ports and platforms. A detailed description of the RM4 transmissometer has been reported by Beutner (14). The manufacturer's literature is recommended for a description of the RM41P (15).

The plume opacities were measured with one or more remote instrumental methods. The trained observer (EPA reference Method 9) method was also used at some plants. The instrumental methods include laser radar (lidar) and contrasting target telephotometry.

The lidar plume opacity measurement is made by beaming a short pulse of laser light through the plume and measuring the amount of light back-scattered from the pulse by the atmosphere in back of the plume relative to the amount back-scattered by the atmosphere in front of the plume. This ratio (R) is a

measure of the two-way transmittance of the plume. The opacity of the plume is  $(1 - \sqrt{R})$ . The method was first proposed and demonstrated by the Stanford Research Institute (16). The lidar is shown in Figure 3. Its design and operational characteristics are shown in Table 2. A complete description of the lidar system and its operation, are given in reports on its development (17,18).

The contrasting target telephotometry method is used to measure the opacity of a plume only when contrasting targets can be viewed through the plume at the stack exit and when the ambient illumination of the plume and targets are stable. The contrasting targets may be distant hills, tall buildings, or towers and the sky adjacent to them. The plume opacity is determined by using a narrow angle-view (less than  $1/2^\circ$ ) telephotometer to measure the ratio of the luminance difference between targets when viewed through and beside the plume. Plume opacity measurement by telephotometry of contrasting targets have been described in detail (19).

The trained observer method of measuring plume opacity is the method generally used by control agencies; it is also the opacity compliance test method used by EPA. The observer measurements were made by certified personnel using the procedures described in the Federal Register (20).

#### PARTICULATE MASS MEASUREMENT

The mass concentration of the particulates in the effluents was determined by sampling the effluents with an EPA Method 5 sampling train, which is described in detail in the Federal Register (21). Any variations from the Federal Register procedures will be noted when discussing the plant tests below.

#### PARTICLE SIZE MEASUREMENT

The size of the emission particles was measured by size selective sampling using cascade impactors. Two source test impactors were employed during the study: the Anderson Model III and the Pilat Mark III. The impactors are similar in size and are both inserted into the stack through standard 10-Cm (4-in) sampling ports for in-situ sampling of effluent. They are usually

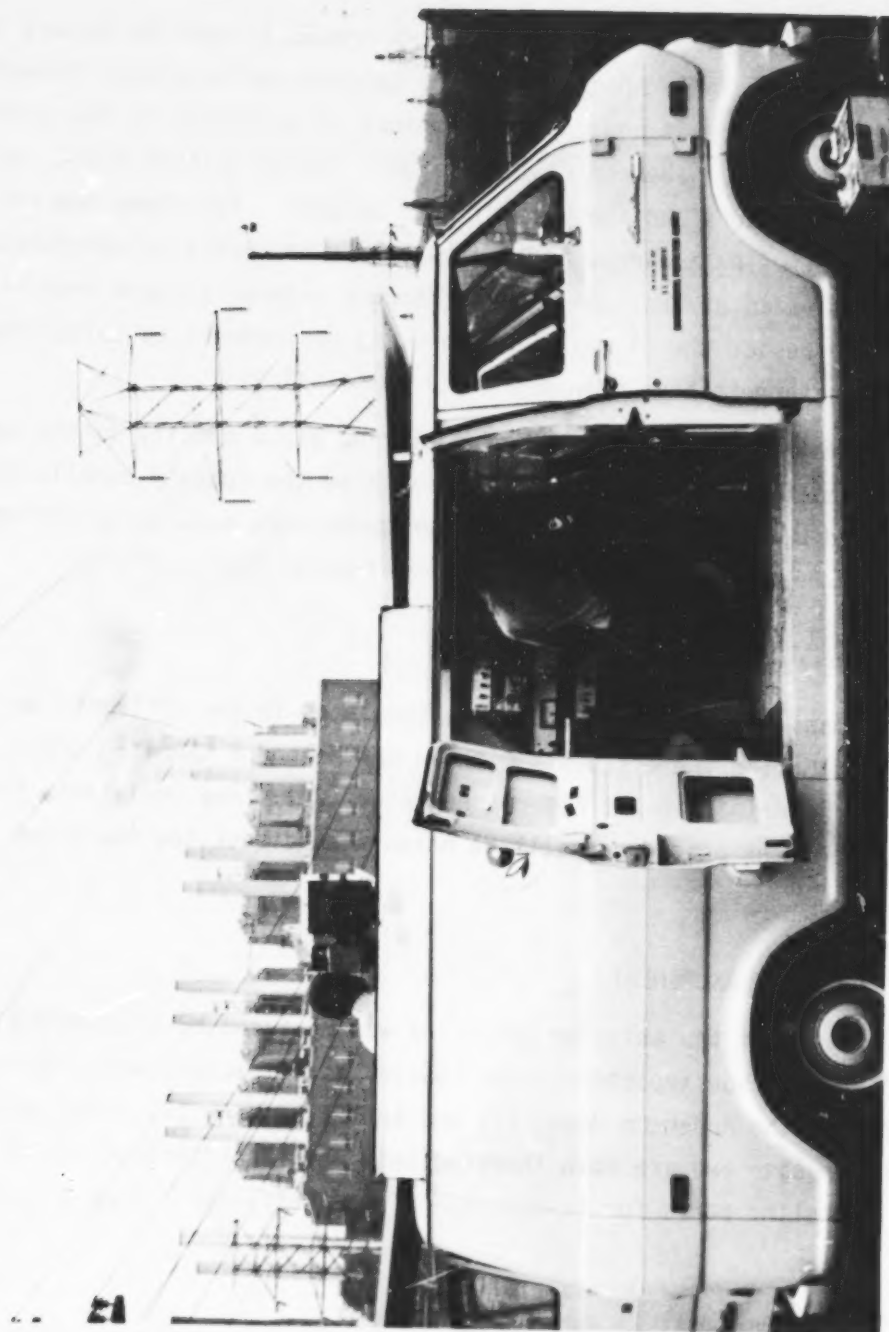


Figure 3. Photograph of mobile lidar system.

TABLE 2. MOBILE LIDAR SYSTEM CHARACTERISTIC

| TRANSMITTER        |  |                                  |
|--------------------|--|----------------------------------|
| Component          |  | Characteristic                   |
| Laser              |  | Rotating prism, Q-switched ruby  |
| Wavelength         |  | 694.3 nm                         |
| Pulse width (FWHH) |  | < 30 nsec                        |
| Maximum output     |  | 1.0 joule                        |
| Repetition rate    |  | 3 pulses/min                     |
| Cooling            |  | Deionized water                  |
| Objective lens     |  | 12.7 cm, f/5                     |
| Beam divergence    |  | $\sim 0.5$ miliradian full angle |
| RECEIVER           |  |                                  |
| Component          |  | Characteristic                   |
| Objective lens     |  | 15.25 cm, f/5                    |
| Field-of-view      |  | 4 miliradian full angle          |
| Bandpass (FWHH)    |  | 1.2 nm                           |
| Photomultiplier    |  | IT&T F4084 (modified S-20)       |
| Off-gating         |  | $\leq 60$ dB                     |
| Response           |  | $\sim 100$ nsec                  |

operated within a flow rate range of 14 to 28 l/min; both accept an assortment of straight or "gooseneck" nozzle sizes to permit isokinetic sampling. The Pilat impactor consists of seven impactor stages (and "back-up" filter) with size cuts ranging from 0.27 to 23  $\mu$ m diameter and the impaction surfaces are 1 to 2 mill stainless steel shim stock coated with polyethylene glycol to improve particle adhesion. The Anderson impactor consists of eight impactor

stages (and "back-up" filter) with size cuts ranging from 0.52 to 13  $\mu\text{m}$  diameter. The impaction stages of the Anderson are designed to use glass fiber filters as the impaction surfaces. In this case, adhesion is due to penetration of the particles into the filters. A comparative evaluation of impactors at a coal-fired power plant indicated similar performances for the Anderson and Pilat impactors (22).

The procedures for collecting size selective samples with the impactor are very similar to the EPA Method 5 procedures for determining mass loading. The criteria for determining the preferred sampling locations, number of traverse points, flow rate, and nozzle size selection for isokinetic sampling are the same. In the case of source test impactors, they must be allowed to reside in the effluent for sufficient time prior to sampling in order to obtain a temperature equilibrium (approximately 30 minutes for these impactors). It is also necessary to maintain a constant sample flow rate through the impactor during a test (to maintain constant impactor size separating characteristics), and not collect too large a sample, overloading the stages. Additional information on the impactors is given in the manufacturer's literature (23,24).

#### MULTIWAVELENGTH OPACITY MEASUREMENT

The opacity of the emissions was measured for different colors of light within the visible spectrum with a dual wavelength sun photometer. The sun photometer method of determining plume opacity requires measurement of the relative intensity of the sun when viewed beside and through the plume with the photometer. Clearly, this procedure requires the sun not be obstructed by clouds and the shadow of the plume be in an accessible location. Accurate opacity measurements also require that the sun be viewed through a defined cross section of the plume. However, for this study, where only relative measurements were required, two sun photometers operating at different wavelengths were coupled and operated together as a unit to obtain concurrent opacity-wavelength measurements; consequently, a well-defined plume cross section was not necessary. Detailed information on dual wavelength sun photometer instrumentation, and its application to extinction-wavelength ratio measurements of plumes can be found in Reference 19.

## SECTION 6

### CEMENT PLANT TESTS

#### TEST SITES

Opacity measurements were conducted at four cement plants. Plants I, II, and III used the wet-process rotary kiln production method and electrostatic precipitator dust collectors. Plant IV used the dry-process rotary kiln production method and a baghouse dust collector. In-stack opacity measurements were made at each plant by a transmissometer. In addition to the in-stack opacity measurements, concurrent plume opacity measurements were made at Plants I and II. The plume opacity measurements at Plant I were made by lidar and trained observer, and by sun photometer at two wavelengths. The plume opacity measurements at Plant II were made by contrasting target telephotometry; the in-stack opacity measurements by "permanent" transmissometer.

Concurrent measurements were also taken of the mass concentration and size of the particulate emissions at Plants II, III, and IV. The mass concentration measurements were made by traverse sampling with the Method 5 train, the size measurements with the cascade impactors. At each plant, the in-stack monitoring of particulate opacity and the extraction of particulate samples were at adjacent locations in the stack.

At Plant II, the in-stack measurements were made at the 32-m (105-ft) level of a 45.7-m (150-ft) high stack. The inside diameter of the stack at the sampling location was 4.3-m (14 ft). The sampling location was 6.1-m (20 ft) above the stack inlet and 13.7-m (45 ft) below the stack outlet (see Figure 4).

To extract particulate samples, a set of four 10-cm (4-in) diameter ports were located at 90° intervals around the stack. To monitor opacity, a Lear Siegler RM4 transmissometer was located on the stack approximately 30-cm (1 ft) above and at a 45° angle to the sampling ports.

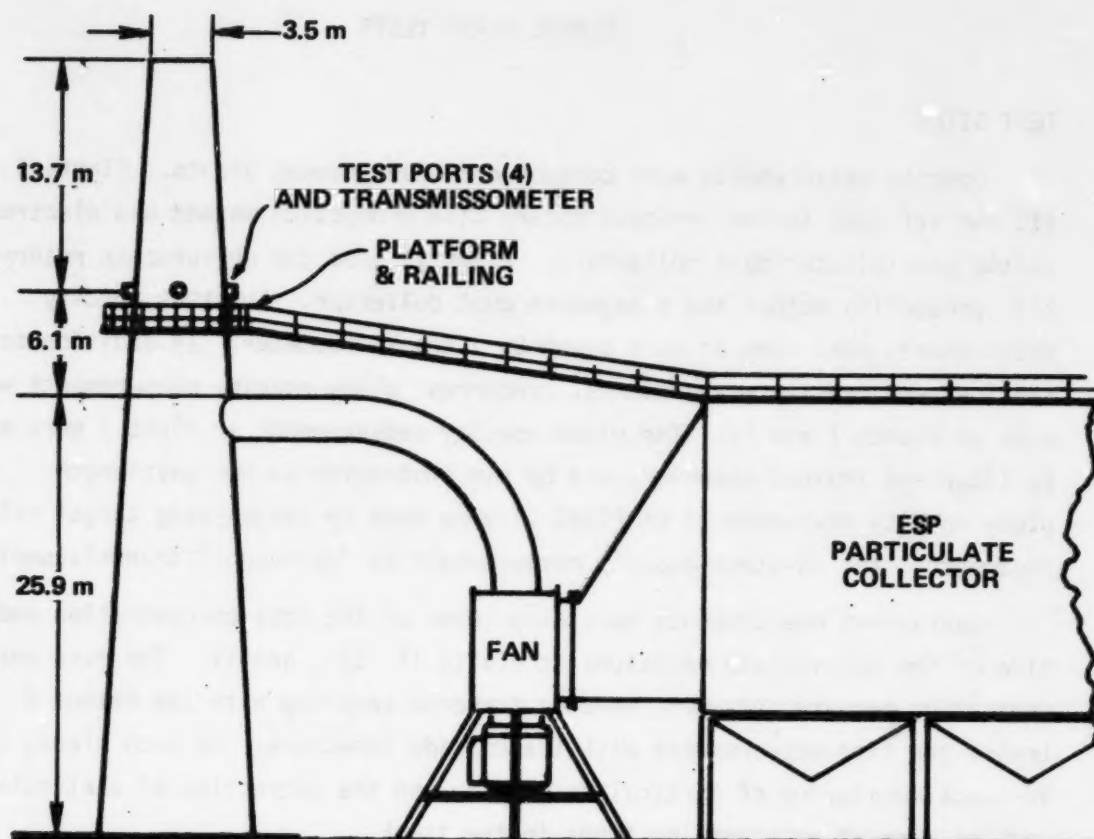


Figure 4. Schematic of cement plant test site II.

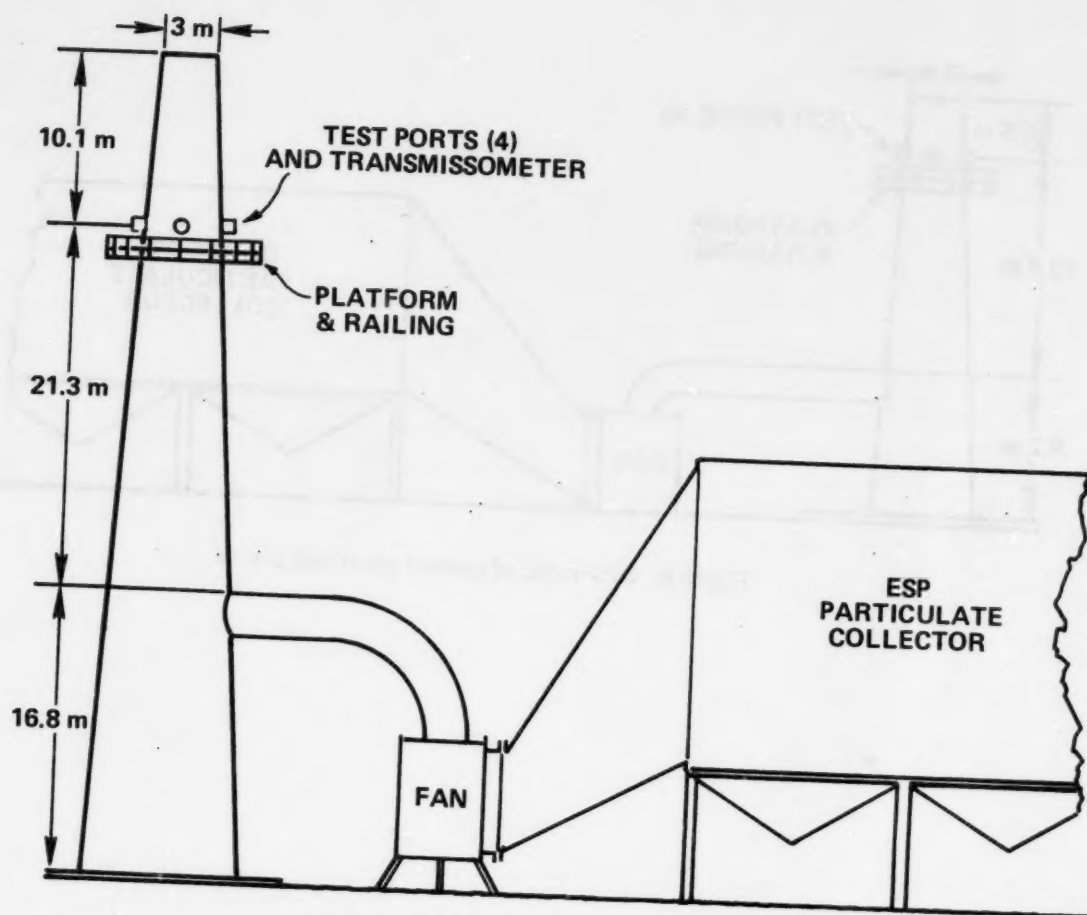


Figure 5. Schematic of cement plant test site III.

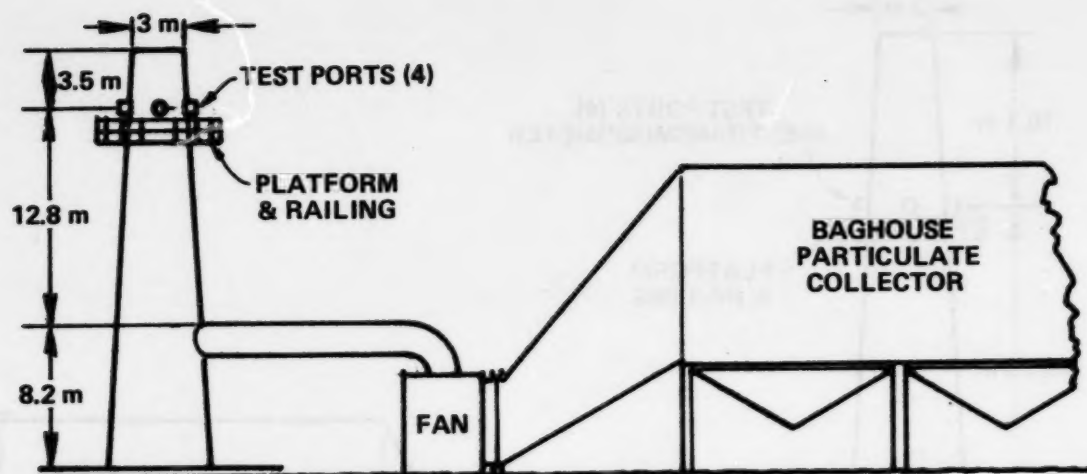


Figure 6. Schematic of cement plant test site IV.

At Plant III, the measurements were made at the 38.1-m (125-ft) level of a 48.2-m (158-ft) high stack. The inside diameter of the stack at the sampling location was 3.7 m (12 ft). The sampling location was approximately 21.3-m (70 ft) above the stack inlet and 10.1-m (33-ft) below the stack outlet (see Figure 5). To extract particulate samples, a set of four 10-cm (4-in) diameter ports were located at 90° intervals around the stack. To monitor opacity, a Lear Siegler RM4 transmissometer was located on the stack approximately 30-cm (1-ft) above and essentially in line with two opposing sampling ports.

At Plant IV, the measurements were made at the 21.0-m (69-ft) level of a 24.4-m (80-ft) high stack. The inside diameter of the stack at the sampling locations was 3.0 m (10 ft). The sampling location was 12.8-m (42-ft) above the stack inlet and 3.4-m (11-ft) below the stack outlet (see Figure 6). To extract particulate samples, a set of four 10-cm (4-in) diameter ports were located at 90° intervals around the stack. To monitor opacity, a Lear Siegler RM41-P portable transmissometer was inserted in one of the sampling ports.

## RESULTS AND DISCUSSION

### Design Specifications

The sun photometer measurements of the blue and red light opacity of the plume emitted by cement Plant I (see Table 3) showed that the opacity of the plume did not vary as a function of the wavelength of the light in the visible part of the spectrum. Consequently, the promulgated specification for spectral response is more than adequate for the transmissometer used to monitor the opacity of cement plant emissions. The cement plant particle size measurements (see Tables 4, 5, 6, and Figure 7) indicate that the promulgated spectral response specification is more than adequate for cement plants. These data showed the mass mean particle size of the emissions to be near 2  $\mu\text{m}$  diameter and the distribution of size to be relatively wide. Since the spectral response specification limits the transmissometer response to wavelengths much smaller than 2  $\mu\text{m}$ , a wavelength effect within the specification response limits is not to be expected.

TABLE 3. CEMENT PLANT OPACITY MEASUREMENTS

| Plant | Measurement period, min. | By in-stack transmissometer | Percent opacity |                    | Extinction ratio, blue/red |
|-------|--------------------------|-----------------------------|-----------------|--------------------|----------------------------|
|       |                          |                             | Lidar           | By remote observer |                            |
| I     | 60                       | 11-17                       | 10±4            | 5±1                | 1                          |
| II    | 40                       | 19-23                       | ----            | ---                | ---                        |
|       | 42                       | 18-24                       | ----            | ---                | ---                        |
|       | 48                       | 7-9                         | ----            | ---                | ---                        |
|       | 47                       | 6-9                         | ----            | ---                | ---                        |
|       | 55                       | 9-17                        | ----            | ---                | ---                        |
|       | 60                       | 9-12                        | ----            | ---                | ---                        |
|       | 42                       | 13-17                       | ----            | ---                | ---                        |

<sup>a</sup>Measurement ~ 1/2 stack diameter (2-3 m) above stack exit. Data are mean ± 95 percent confidence interval of measurement set.

The particle size data indicated as well that the collimation specifications for transmissometers are adequate for cement plants. For 2  $\mu\text{m}$  diameter monodisperse particles, a transmissometer with the maximum allowable five degree collimation angles would be expected to measure opacity about 2 percent opacity low at 20 percent opacity; a true (theoretical) opacity of twenty percent would thus be measured as 18 percent opacity. This difference would represent at most an upper limit for cement plants. The relatively wide size distribution of the emissions (3 to 6 geometric standard deviation) would reduce the difference to within 1 percent opacity at a theoretical opacity of 20.

#### Performance Specifications

The in-stack transmissometer performance relative to zero and span drift stability at the cement plants was good. No significant drift was observed over monitoring periods up to 1 month. No problem related to the process was observed that would prevent stable operation and preclude the application of the promulgated drift specification to cement plants. The observed zero and span drifts were less than the 2 percent opacity specifications and related primarily to the stability of the instrument used for the measurement, to the adequacy of its air purge system, and to the adequacy of the instrument installation on the stack.

#### In-Stack and Plume Opacity

The data of in-stack and plume opacity measurements at cement Plants I and II are shown in Table 3. At Plant I, the data showed that the average of a set of 13 plume opacity measurements made by lidar was 4 percent opacity lower than the average in-stack opacity measured by portable transmissometer, and that the average of a set of 38 plume opacity measurements made by trained observer was 9 percent opacity lower than the average in-stack opacity measured by the portable transmissometer. These measurements were made late in the day (near dusk), during a 30-minute period of relatively steady plant operation. The low observer readings may have resulted from poor plume visibility.

Sun photometer opacity measurements, which were made at Plant I during an earlier 6-minute time period before the in-stack transmissometer was operating, averaged 14 percent opacity for both blue and red light. This

TABLE 4. Portland Cement Plant II  
Anderson Impactor Data

| Stage No. | D50 Cut, $\mu\text{m}$ | Percent of total sample weight by stages |        |        |        |        | Average |
|-----------|------------------------|------------------------------------------|--------|--------|--------|--------|---------|
|           |                        | Test 1                                   | Test 2 | Test 3 | Test 4 | Test 5 |         |
| 1         | 13                     | 21                                       | 8      | 5      | 8      | 15     | 11      |
| 2         | 8.2                    | 9                                        | 7      | 11     | 8      | 3      | 8       |
| 3         | 5.4                    | 14                                       | 10     | 4      | 7      | 13     | 10      |
| 4         | 3.8                    | 9                                        | 9      | 6      | 7      | 3      | 7       |
| 5         | 2.4                    | 14                                       | 10     | 8      | 5      | 4      | 8       |
| 6         | 1.25                   | 16                                       | 16     | 19     | 21     | 55     | 25      |
| 7         | 0.75                   | 10                                       | 16     | 26     | 24     | 5      | 16      |
| 8         | 0.52                   | 6                                        | 11     | 9      | 12     | 4      | 8       |
| F         | ---                    | 1                                        | 13     | 12     | 8      | 2      | 7       |

TABLE 5. Portland Cement Plant III  
Anderson Impactor Data

| Stage No. | D50 Cut, $\mu\text{m}$ | Percent of total sample weight by stages |        |        |        |        | Average |
|-----------|------------------------|------------------------------------------|--------|--------|--------|--------|---------|
|           |                        | Test 1                                   | Test 2 | Test 3 | Test 4 | Test 5 |         |
| 1         | 13                     | 2                                        | 8      | 7      | 4      | 6      | 5       |
| 2         | 8.2                    | 16                                       | 6      | 14     | 9      | 5      | 10      |
| 3         | 5.3                    | 22                                       | 8      | 20     | 7      | 9      | 13      |
| 4         | 3.8                    | 22                                       | 16     | 9      | 6      | 8      | 12      |
| 5         | 2.4                    | 14                                       | 12     | 5      | 8      | 9      | 10      |
| 6         | 1.25                   | 4                                        | 5      | 7      | 5      | 9      | 7       |
| 7         | 0.75                   | 9                                        | 12     | 6      | 26     | 10     | 13      |
| 8         | 0.52                   | 6                                        | 13     | 12     | 17     | 19     | 13      |
| F         | ---                    | 5                                        | 20     | 20     | 18     | 28     | 17      |

TABLE 6. Portland Cement Plant IV  
Pilat Impactor Data

| Stage No. | D50 Cut, $\mu\text{m}$ | Percent of total sample weight by stages |        |        |        |        |        | Average |
|-----------|------------------------|------------------------------------------|--------|--------|--------|--------|--------|---------|
|           |                        | Test 1                                   | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 |         |
| 1         | 23                     | 18                                       | 27     | 13     | 15     | 10     | 6      | 15      |
| 2         | 10                     | 7                                        | 15     | 7      | 7      | 8      | 5      | 8       |
| 3         | 4.7                    | 35                                       | 29     | 36     | 34     | 18     | 16     | 28      |
| 4         | 1.9                    | 25                                       | 20     | 30     | 29     | 34     | 41     | 30      |
| 5         | 1.0                    | 11                                       | 7      | 12     | 10     | 20     | 22     | 14      |
| 6         | 0.52                   | 2                                        | 1      | 1      | 3      | 7      | 7      | 3       |
| 7         | 0.27                   | 0                                        | 0      | 0      | 0      | 0      | 0      | 0       |
| F         | ---                    | 2                                        | 1      | 1      | 2      | 3      | 3      | 2       |

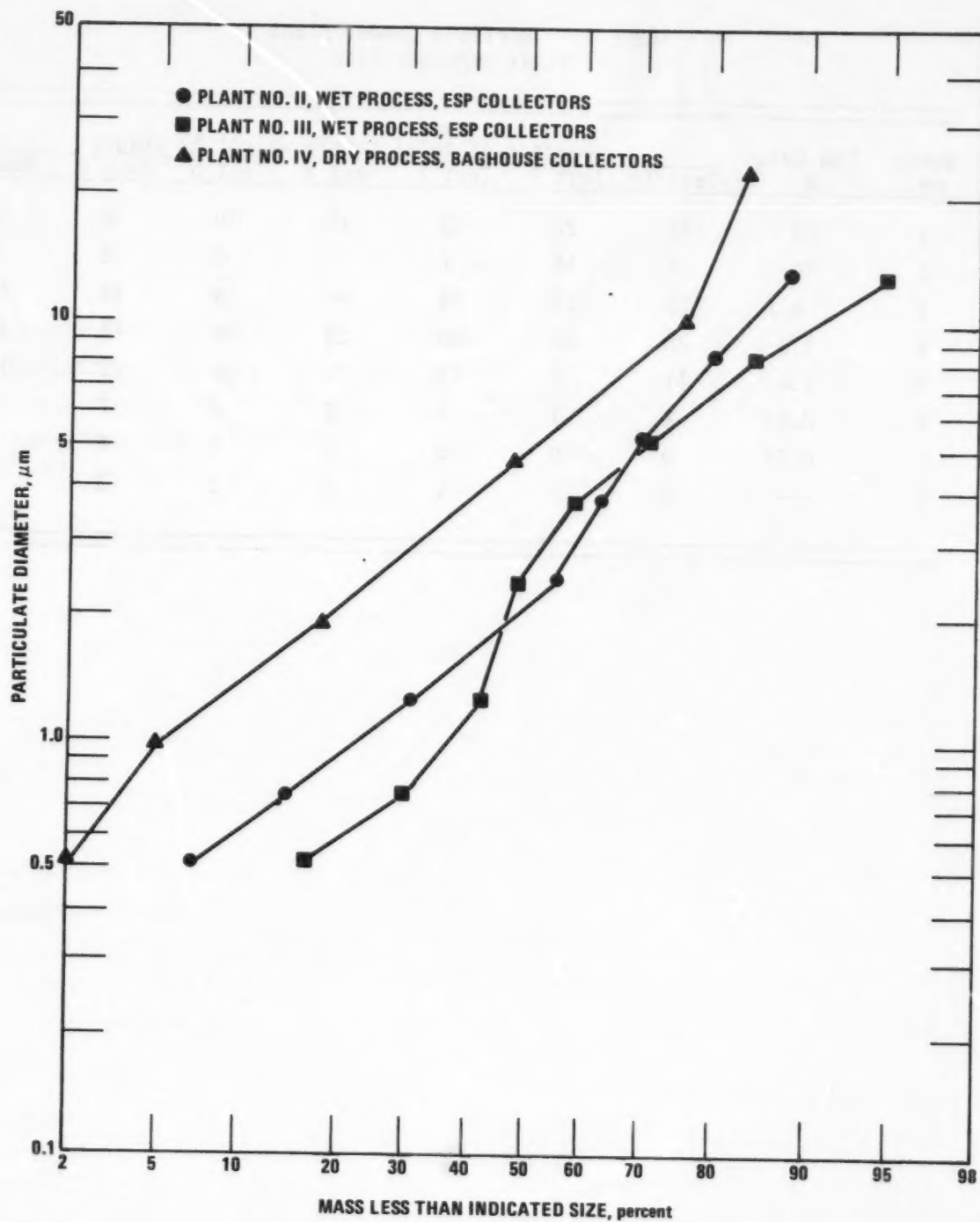


Figure 7. Particle size distributions of Portland cement plants.

result showed that the promulgated spectral response specification for transmissometer opacity monitors is adequate, indicated that the size of the particulate emission is larger than 1 or 2  $\mu\text{m}$  diameter and agrees with the particle size measurements described above.

At Plant II, the data showed that the averages of sets of plume opacity measurements (100 to 150 measurements per set) made by the contrasting target telephotometry method over short periods of time (less than 60 minutes) during relatively steady plant operation were within  $\pm 6$  percent opacity of the mean of the high and low continuous in-stack opacity measurements obtained by transmissometer over the same time periods. The differences were random, indicating no systematic variation between the plume and in-stack opacities at the cement plants. The magnitude of the difference ( $\pm 6$  percent) was in part due to difficulty in making the remote telephotometer measurements. A telephotometer opacity measurement requires about 4 seconds to execute and should be made during steady plume conditions of opacity, lighting, and background. The conditions were often not good for the measurement. With good conditions agreement better than 2 to 3 percent opacity cannot be expected.

On cold days condensation could occur in the plumes of the cement plants, producing higher plume opacities. The presence of condensation was usually obvious from the appearance plume. Depending on ambient temperature, the condensation plume could be attached or detached from the stack. No condensation was observed in-stack during cold weather.

#### In-Stack Opacity and Mass Concentration

The comparisons of in-stack light attenuation and mass concentration measurements at cement Plants II, III, and IV are shown in Figure 8 for the mass concentration measurements at standard conditions and dry gas. Figure 9 depicts the same data with the mass concentration measurements at actual stack conditions. Also shown in Figures 8 and 9 are linear regression lines of data reported by Buhne (25) in 1972 for a dry process cement plant with electrostatic precipitator emission controls. These data indicated that the light attenuation coefficient of the particulate emissions at cement plants is linearly related to the mass concentration of the particulate emissions for both dry and wet process cement production. For mass concentration data

at standard conditions and dry gas (see Figure 8), the slopes of the curves (attenuation coefficient/mass concentration,  $\text{m}^{-1}/\text{g}/\text{m}^3$ ) for standard conditions are all within  $0.57 \pm 0.10$ .

When the mass concentration data were for actual conditions (see Figure 9), the slopes of the curves were distinctly different for the wet and dry processes. The slopes are represented by  $1.55 \pm 0.02 \text{ M}^{-1}/\text{g}/\text{m}^3$  averaged for the wet processes and  $0.92 \pm 0.08$  averaged for the dry processes. The slopes of all data for actual conditions are within  $1.2 \pm 0.4$ .

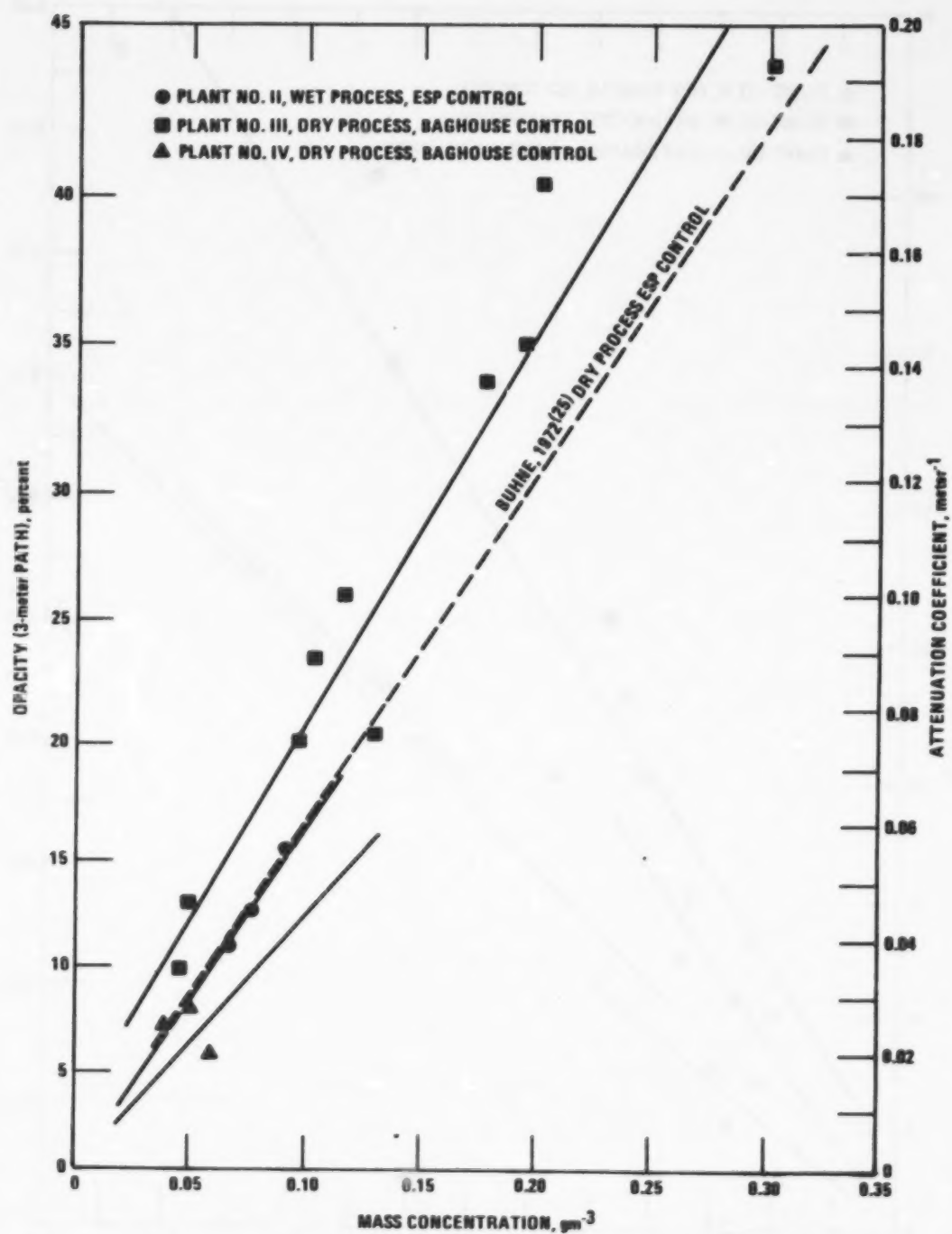


Figure 8. In-stack opacity of emissions from Portland cement plants as a function of the mass concentration of the particulates at standard conditions and dry gas.

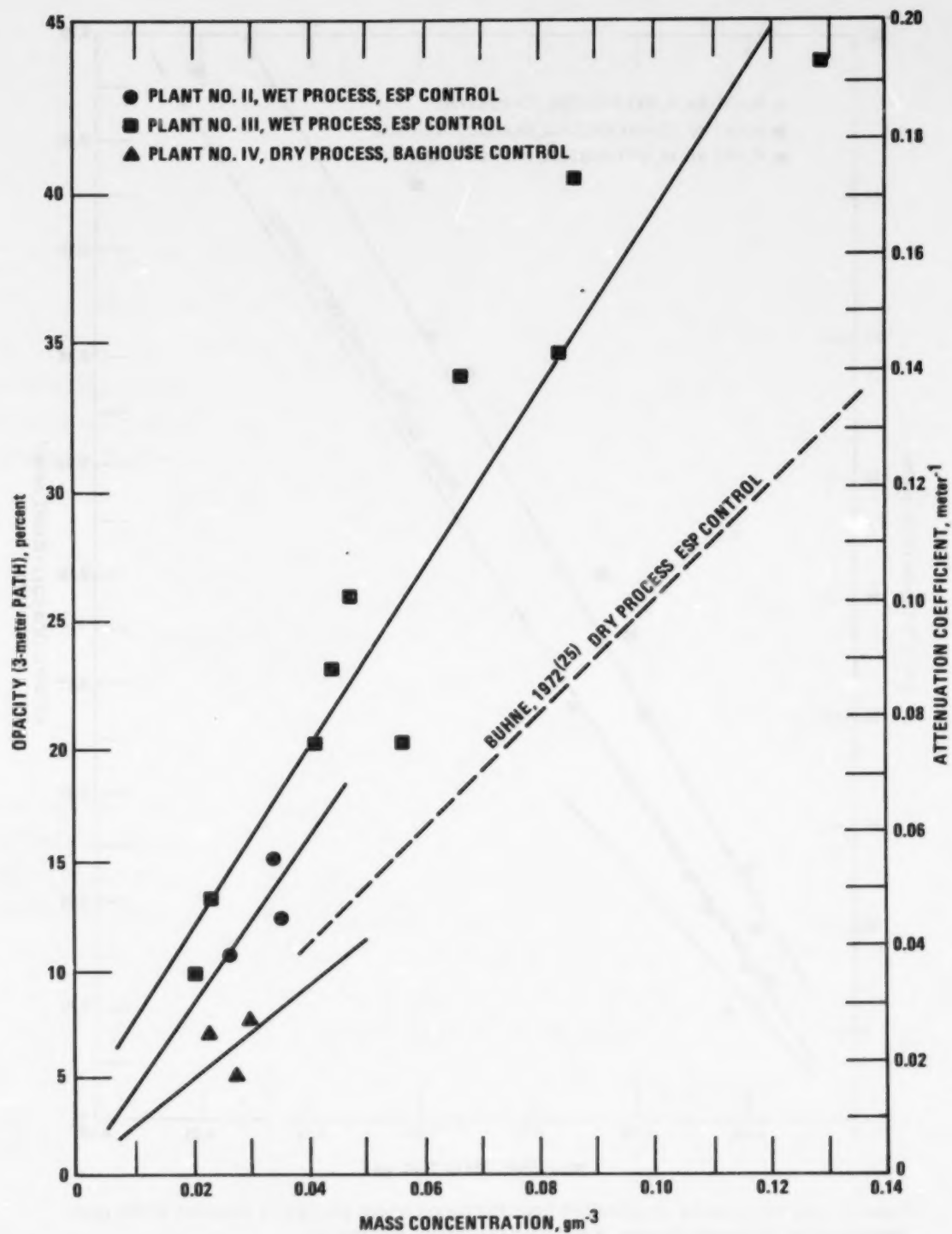


Figure 9. In-stack opacity of emissions from Portland cement plants as a function of the mass concentration of the particulates at actual conditions.

## SECTION 7

### OIL-FIRED POWER PLANT TESTS

#### TEST SITES

Opacity measurements were conducted at three oil-fired power plants of different sizes. They all burned residual fuel oils with an additive to inhibit corrosion and none had emission control equipment. Plant I was a 70 megawatt unit burning medium sulfur ( $\sim 1.5\%$  by weight) residual fuel oil. Plant II was a 190 megawatt unit burning medium sulfur ( $\sim 1.0\%$  by weight) residual fuel oil. Plant III was a 520 megawatt unit burning high sulfur ( $\sim 2.5\%$  by weight) residual fuel oil. Plants I and II normally operated at excess oxygen boiler firing levels of 1.5 and 3 percent, respectively. However, the boiler at Plant III was specially designed to normally operate at a very low excess oxygen level of 0.2 percent. None of the plants utilized emission control equipment.

In-stack opacity, plume opacity, particulate mass concentration, and size measurements were made at each plant. The in-stack opacity measurements were made by transmissometer. The plume opacity measurements were made by lidar, trained observer, and sun photometer at two wavelengths. The particulate mass concentration and size measurements were made by sampling the emissions with a Method 5 train and a Pilat Mark III cascade impactor. At each plant the in-stack monitoring of particulate opacity and the extraction of particulate samples were at adjacent locations in the stack.

At Plant I the in-stack measurements were made at the 43-m (141-ft) level of a 45.6-m (150 ft) high stack. The inside diameter of the stack at the sampling location was 3.3-m (10.8-ft). The sampling location was 16.7-m (55-ft) above the stack inlet and 2.7-m (9-ft) below the stack outlet (see Figure 10). To extract particulate samples, a set of three 10-cm (4-in)

diameter ports were located at 45° intervals around the stack. A Lear Siegler RM41-P portable transmissometer was installed in the center port to monitor opacity. The remaining 90° ports were used for particulate sampling.

At Plant II, the in-stack measurements were made at the 26-m (85-ft) level of a 61-m (200-ft) high stack. The inside diameter of the stack at the sampling location was 3-m (10-ft). The sampling location was 5-m (15-ft) above the stack inlet and 35-m (113ft) below the stack outlet (see Figure 11). To extract particulate samples, two opposing 10-cm (4-in) diameter ports were located in the stack. A third port was cut in the stack at an angle of about 20° to one of the sampling ports to install a Lear Siegler RM41-P portable transmissometer for opacity monitoring.

At Plant III, the in-stack measurements were in the duct breeching of the stack. The stack was 153-m (500-ft) high with an exit diameter of 5.2-m (17-ft). The breeching was a long horizontal duct (4.3-m wide by 8.4-m high by 51-m long). The in duct sampling location was approximately 160-m from the stack exit, 18-m from the stack inlet and 34-m past the duct inlet (see Figure 12). To extract particulate samples and install a Lear Siegler RM41-P opacity monitor, a vertical array of six 10-cm (4-in) diameter ports were located at 1.4-m intervals on one side of the duct.

## RESULTS AND DISCUSSION

### Design Specifications

The sun photometer measurements of the blue and red light opacity of the plumes emitted by the three plants (see Table 7) showed that the opacity was a function of the wavelength of light in the visible part of the spectrum. The blue (0.45  $\mu\text{m}$ ) to red 0.65  $\mu\text{m}$ ) extinction ratio ranged from 1.9 to 2.8 for the oil-fired power plant emissions.

This difference showed that the extinction of light by the emissions varies as a function of the wavelength of the light and indicated that the green light extinction is proportional to  $\lambda^{-n}$  with  $n$  having a value between 1.7 and 2.8. This observed range in the value of  $n$  is likely due to small differences in the size and composition of the particulates between plants.

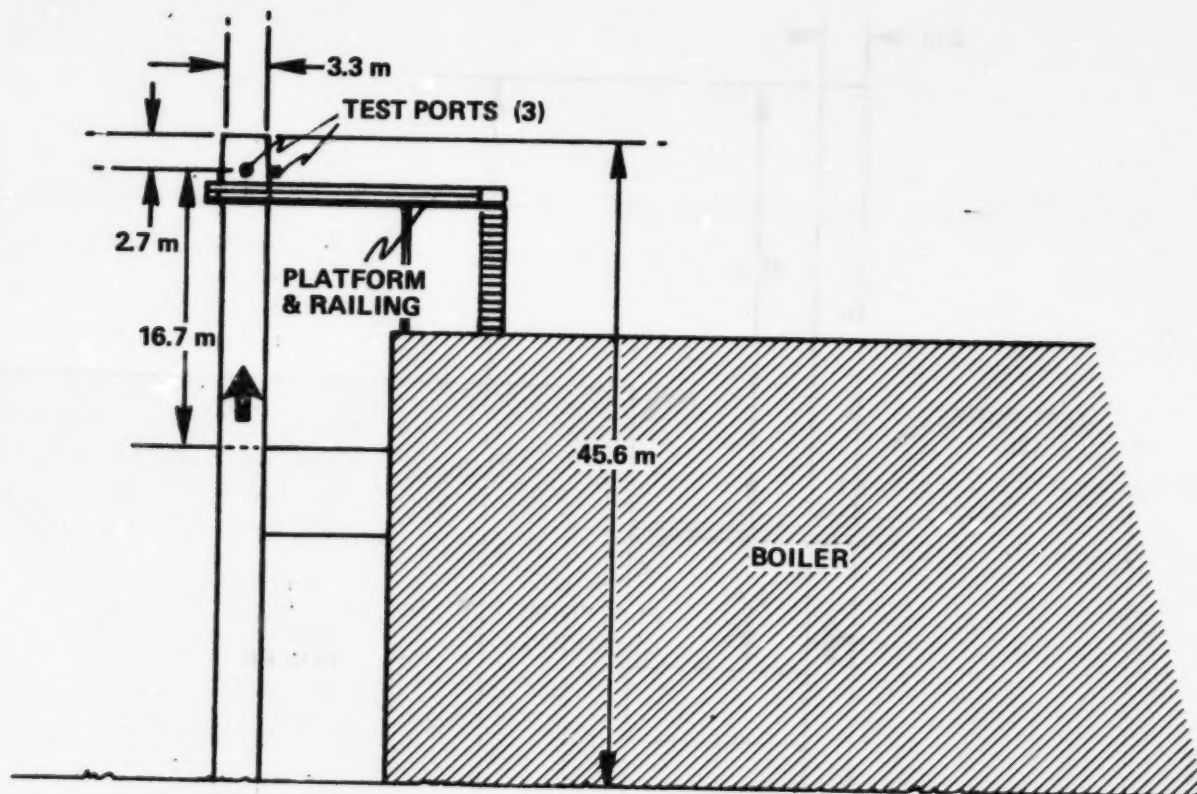


Figure 10. Schematic of oil-fired power plant test site I.

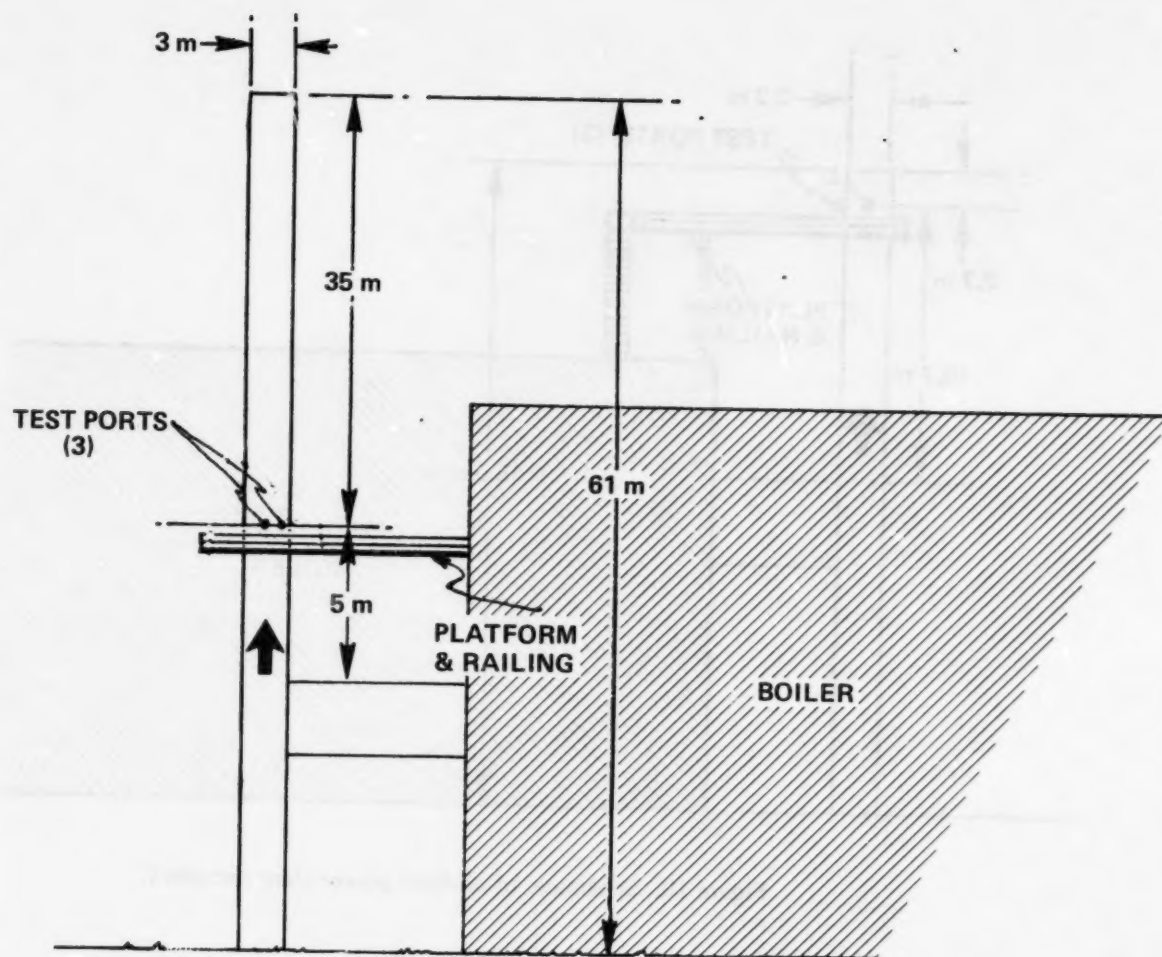


Figure 11. Schematic of oil-fired power plant test site II.

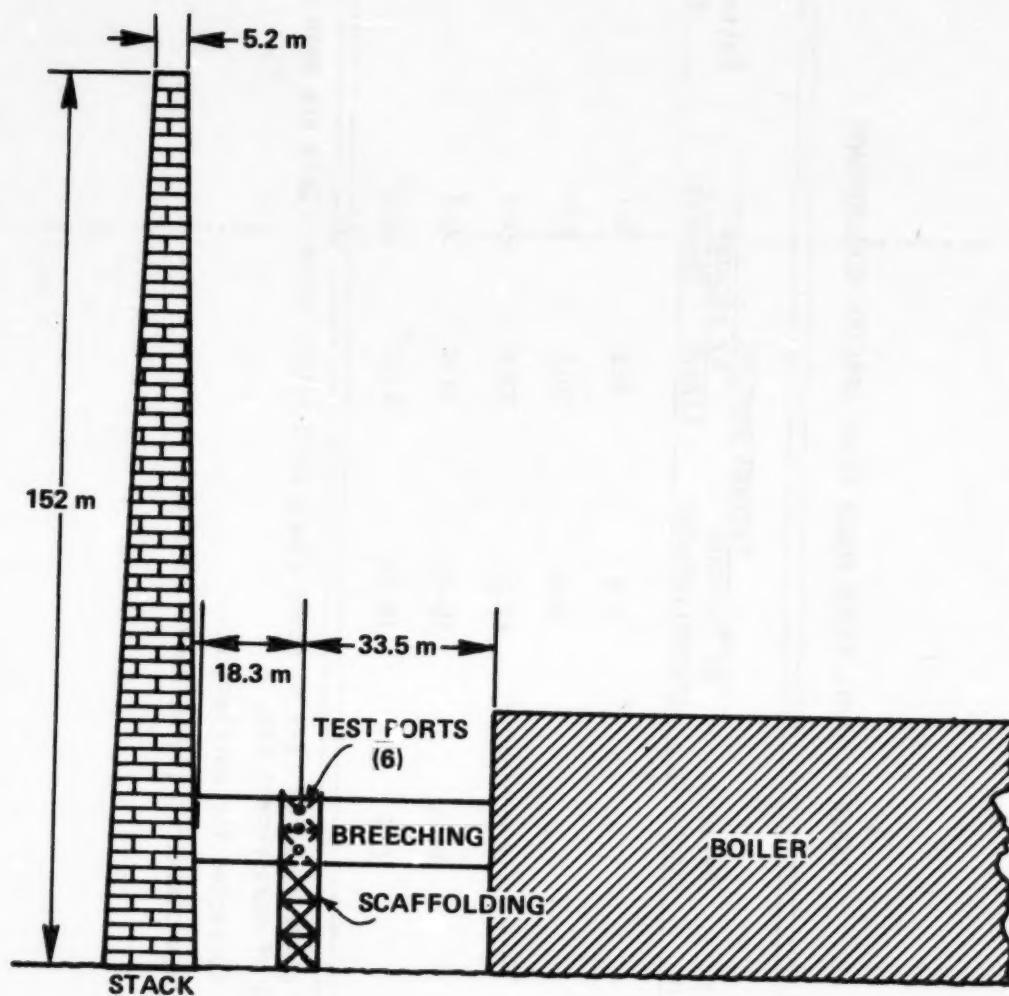


Figure 12. Schematic of oil-fired power plant test site III.

TABLE 7. OIL-FIRED POWER PLANT OPACITY MEASUREMENTS

| Plant | Measurement period, min. | Percent excess O <sub>2</sub> | Percent opacity             |                               |                   | Extinction ratio, blue/red |
|-------|--------------------------|-------------------------------|-----------------------------|-------------------------------|-------------------|----------------------------|
|       |                          |                               | By in-stack transmissometer | By remote <sup>a</sup> Lidarb | Observer          |                            |
| I     | 15                       | 1.5                           | 5-9                         | 8±3                           | 7±1               | 2.8                        |
| II    | 20                       | 6.0                           | 2-3                         | 10±2                          | 6±1               | 2.4                        |
| III   | 35                       | 0.2                           | 17-21                       | 23±4                          | 27±1              | 1.9                        |
|       | 20                       | 0.2                           | 18-22                       | 31±4                          | 30±1              | ---                        |
|       | 15                       | 0.2                           | 18-22                       | 43±3 <sup>c</sup>             | 52±2 <sup>c</sup> | 2.3 <sup>c</sup>           |

<sup>a</sup>Measurements ~ 1/2 stack diameter (2-3 m) above stack exit unless noted. Data are mean ± 95 percent confidence interval of measurement set.

<sup>b</sup>Lidar measurements corrected for wavelength.

<sup>c</sup>Measurements ~ 3 stack diameters (15 m) above stack exit.

For example, a particle size variation of less than 0.2  $\mu\text{m}$  diameter can produce the observed range in  $n$  for these emissions.

For the worst case condition of  $n = 2.8$ , calculation of the opacity that would be measured by transmissometers operating at the promulgated peak response specification limits of 500 and 600 nm, showed a variation of  $\pm 5$  percent opacity relative to a 20 percent opacity measurement (the opacity standard for new oil-fired power plants).

Except for Plant III, the particle size data obtained by sampling with impactors (see Table 8 and Figure 13) indicated that most of the particulate mass in oil-fired power plants emissions is associated with small particles (less than 0.3  $\mu\text{m}$  diameter). The impactor data from Plant III indicated a larger mean size with a considerable amount of mass also associated with large particles around 12  $\mu\text{m}$  diameter. The bimodal size characteristic of Plant III is shown in Figure 14. The reason for the large particle constituent at this plant is attributed to unburned carbon. The plant differed from the others in that it was burning oil with a high sulfur content ( $\sim 2.5$  percent), a high vanadium content ( $\sim 500$  ppm) and operated at a low excess oxygen level of  $\sim 0.2$  percent. The fine particle impactor observations support the observation that the transmittance of the emissions varies with wavelength (see Table 7).

Although the impactor data at Plant III did show a large particle component, the multiwavelength measurements at Plant III showed that the fine particle component in the effluent dominates its optical characteristics and opacity. However, the variation in the transmittance of the emission with wavelength is slightly less than that observed at the other plants and reflects the presence of the larger particles. The collimation specification limits of  $5^\circ$  are more than adequate for oil-fired power plants due to the small particle size of the emissions.

#### Performance Specification

The in-stack transmissometer performance relative to zero and span drift stability at oil-fired power plants was good. No significant drift was observed over monitoring periods up to 1 month, and no problems related to

TABLE 8. Oil-Fired Power Plant  
Pilot Impactor Data

| Plant | Test    | Percent of total sample weight collected<br>on respective D50 ( $\mu$ m) stages of impactor |      |     |     |     |      |      | F  |
|-------|---------|---------------------------------------------------------------------------------------------|------|-----|-----|-----|------|------|----|
|       |         | 23                                                                                          | 10   | 4.7 | 1.9 | 1.0 | 0.52 | 0.27 |    |
| I     | 1       | 2                                                                                           | 28   | 8   | 3   | 2   | 5    | 5    | 47 |
|       | 2       | 3                                                                                           | 5    | 4   | 5   | 4   | 8    | 16   | 55 |
|       | Average | 1.5                                                                                         | 16.5 | 6   | 4   | 3   | 6.5  | 11.5 | 51 |
| II    | 1       | 3                                                                                           | 4    | 2   | 5   | 4   | 4    | 19   | 59 |
|       | 2       | 1                                                                                           | 4    | 2   | 2   | 2   | 3    | 13   | 76 |
|       | 3       | 2                                                                                           | 2    | 2   | 3   | 2   | 2    | 10   | 77 |
|       | 4       | 0                                                                                           | 1    | 2   | 3   | 2   | 2    | 7    | 83 |
|       | 5       | 0                                                                                           | 2    | 1   | 2   | 2   | 3    | 7    | 83 |
|       | Average | 1                                                                                           | 2    | 2   | 3   | 2   | 3    | 11   | 76 |
|       |         |                                                                                             |      |     |     |     |      |      |    |
| III   | 1       | 7                                                                                           | 38   | 6   | 13  | 7   | 2    | 9    | 18 |
|       | 2       | 20                                                                                          | 10   | 6   | 14  | 5   | 3    | 9    | 33 |
|       | 3       | 6                                                                                           | 11   | 4   | 5   | 6   | 7    | 19   | 42 |
|       | 4       | 9                                                                                           | 25   | 10  | 13  | 5   | 3    | 5    | 30 |
|       | 5       | 6                                                                                           | 56   | 12  | 5   | 2   | 1    | 1    | 17 |
|       | Average | 10                                                                                          | 28   | 8   | 10  | 5   | 3    | 9    | 28 |

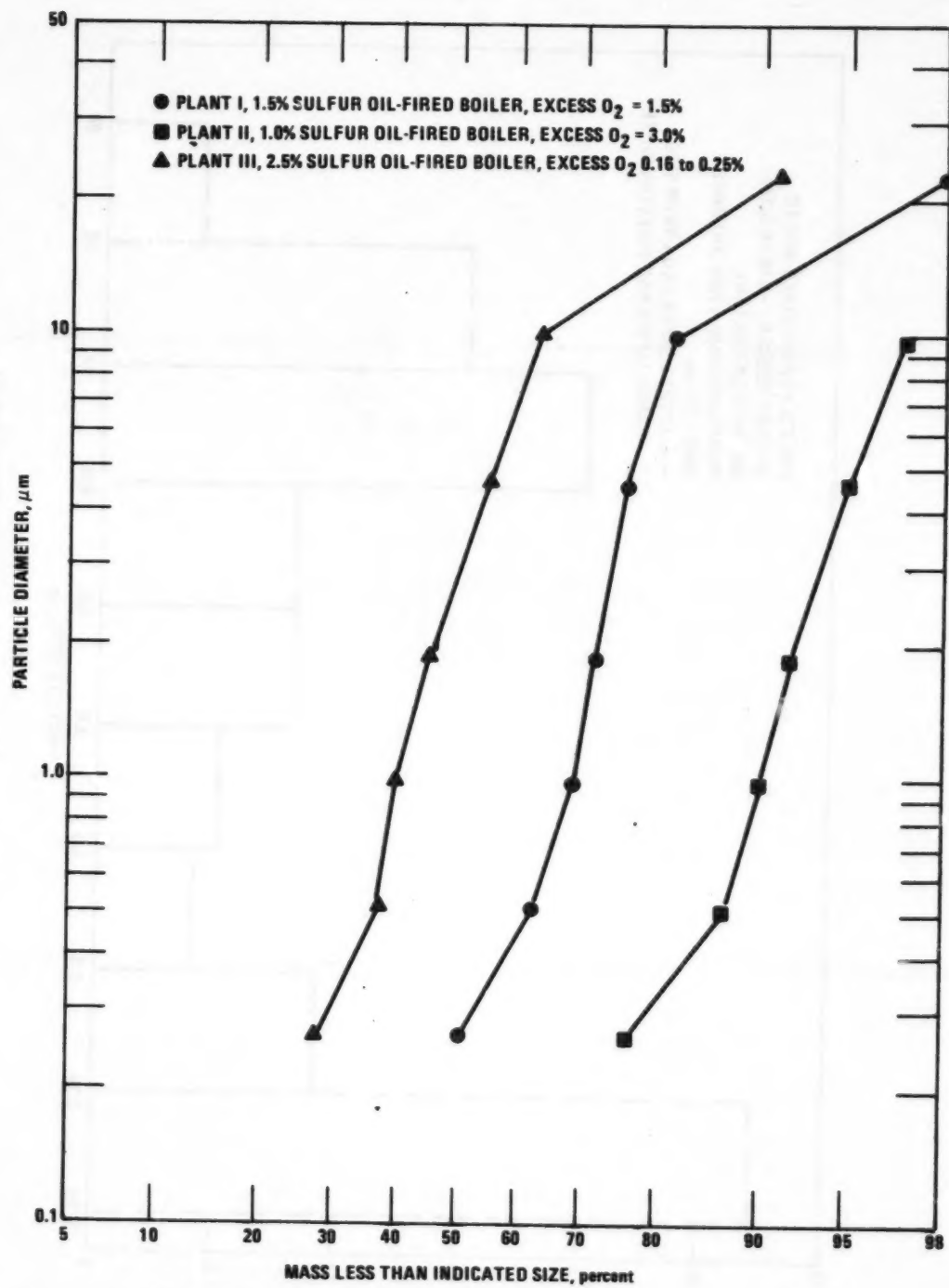


Figure 13. Particle size distributions of oil-fired power plants.

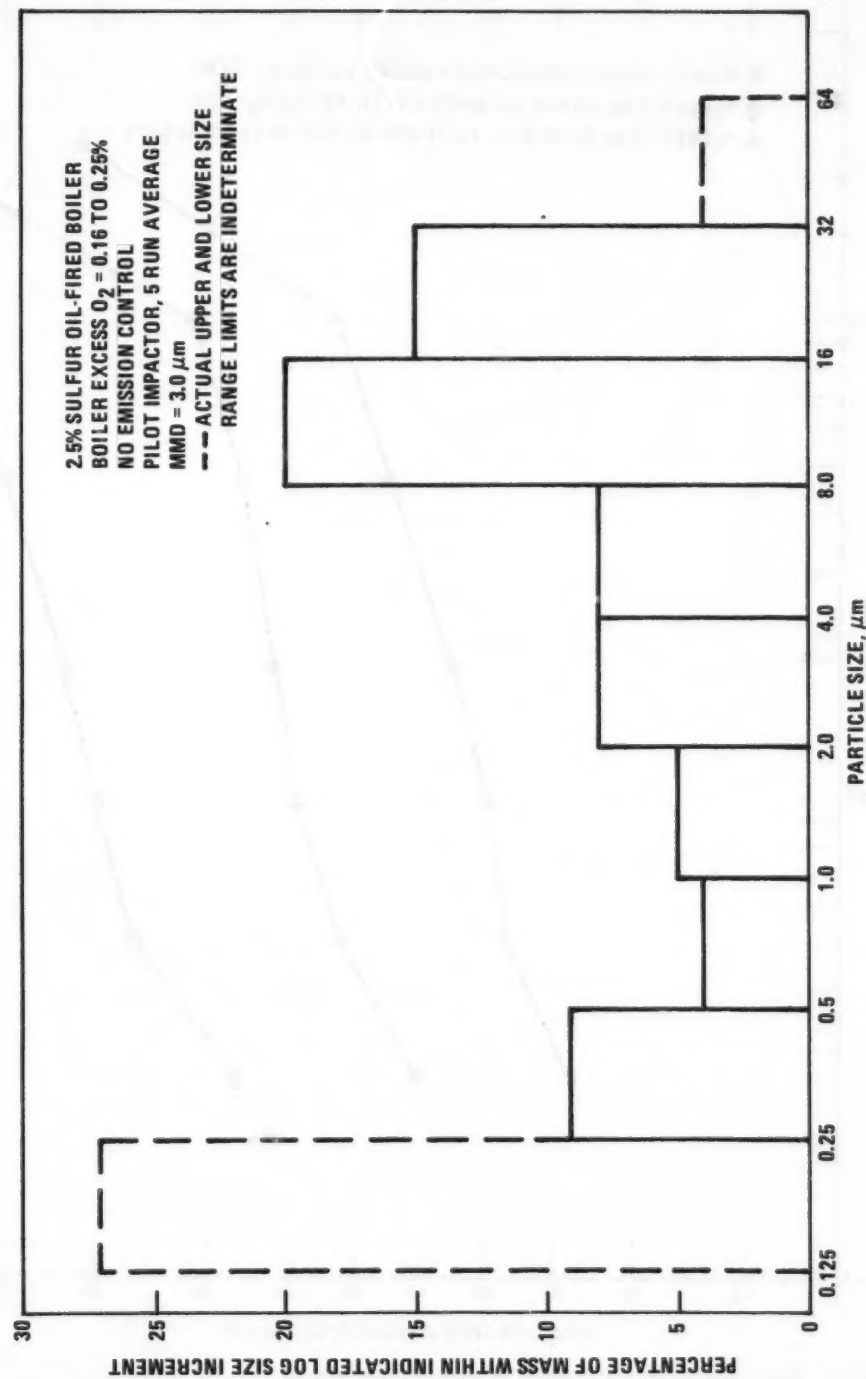


Figure 14. Particle size distribution of oil-fired power plant III.

the process were observed that would prevent stable operation and preclude applying the promulgated drift specifications to oil-fired power plants for monitoring the in-stack opacity by transmissometer.

#### Comparison of In-Stack and Plume Opacity

The comparison of in-stack and plume opacity measurements at the oil-fired power plants (see Table 7) showed that the plume opacities were higher than the in-stack opacities. The measurements were close enough only at Plant I to indicate agreement, but even here, in-stack measurements appeared slightly lower. At the other two plants, the plume opacity measurements were clearly higher than in-stack, and at Plant III measurements several meters up in the plume were higher than in the plume at the stack exit. These data indicated that much of the particulates in the plumes form as the effluent cools in the atmosphere out of the stack. The increase in opacity is attributed to condensation of  $H_2SO_4$  (26). The plant with the most opaque plume and greatest in-stack to plume opacity difference was Plant III, which was burning the high sulfur fuel (2.5 percent). In Table 7, it is interesting to note that the blue/red light extinction measurement of the plume at Plant III was slightly higher several meters up in the plume than at the stack exits. This suggests that the increase in opacity is mostly due to an increase in concentration, not an increase in particulate size.

#### Comparison of In-Stack Opacity and Mass Concentration

The comparison of in-stack light attenuation and mass concentration measurements at oil-fired power plants I, II, and III are shown in Figure 15 for the mass concentration measurements at standard conditions and dry gas, and in Figure 16 for the mass concentration measurements at actual stack conditions. Also shown in Figures 15 and 16 are data reported by Reisman (9) in 1974 for an oil-fired power plant.

Two distinct functional relationships are evident from the data. One relationship concerns the data obtained at Plants I and II and the data reported by Reisman. These plants all burned low-sulfur oil (less than 1.5 percent by weight) and boiler firings were at normal excess oxygen levels between 1.5 and 3.0 percent. The data indicated that the correlation is

linear. The light attenuation coefficient per mass concentration ratios were 0.34 and  $0.43 \text{ m}^{-1}/\text{g}/\text{m}^3$  with the mass concentration measurements at standard conditions (dry gas) and actual conditions, respectively.

The second relationship is for data obtained at Plant III for two series of tests. This plant burned high-sulfur oil ( $\sim 2.5\%$  by weight), and boiler firing was at its normal excess oxygen level of 0.2 percent. The light attenuation coefficient per mass concentration ratio at this plant was 0.11 and  $0.20 \text{ m}^{-1}/\text{g}/\text{m}^3$  with the mass concentration measurements at standard conditions (dry gas) and actual conditions, respectively.

The low excess oxygen conditions for Plant III as compared to the higher excess oxygen conditions for Plants I and II produced a great portion of particles (unburned carbon) in the large size fractions. The size distributions in Figure 13 show a mass median diameter of about  $3 \text{ }\mu\text{m}$  for Plant III emissions. The value is about an order of magnitude greater than the mass median diameter for Plants I and II emissions. Consequently, the mass concentration vs opacity relationships in Figure 15 are consistent with the physical properties of the emissions. For the same mass concentration, the larger number of submicron particles in Plants I and II emissions produced greater light scatter and gave higher opacity readings.

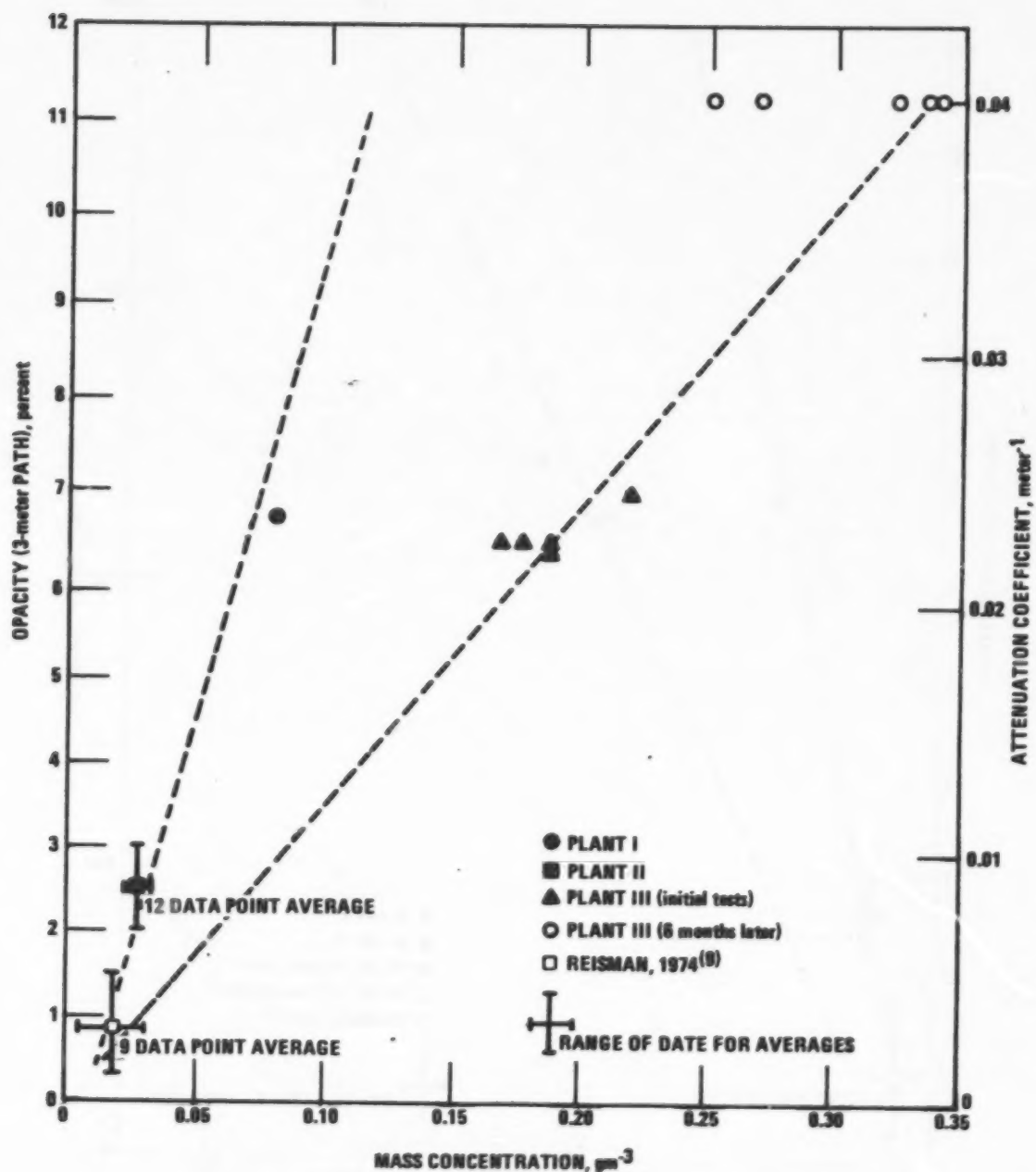


Figure 15. In-stack opacity of emissions from oil-fired power plants as a function of the mass concentration of the particulates at standard conditions and dry gas.

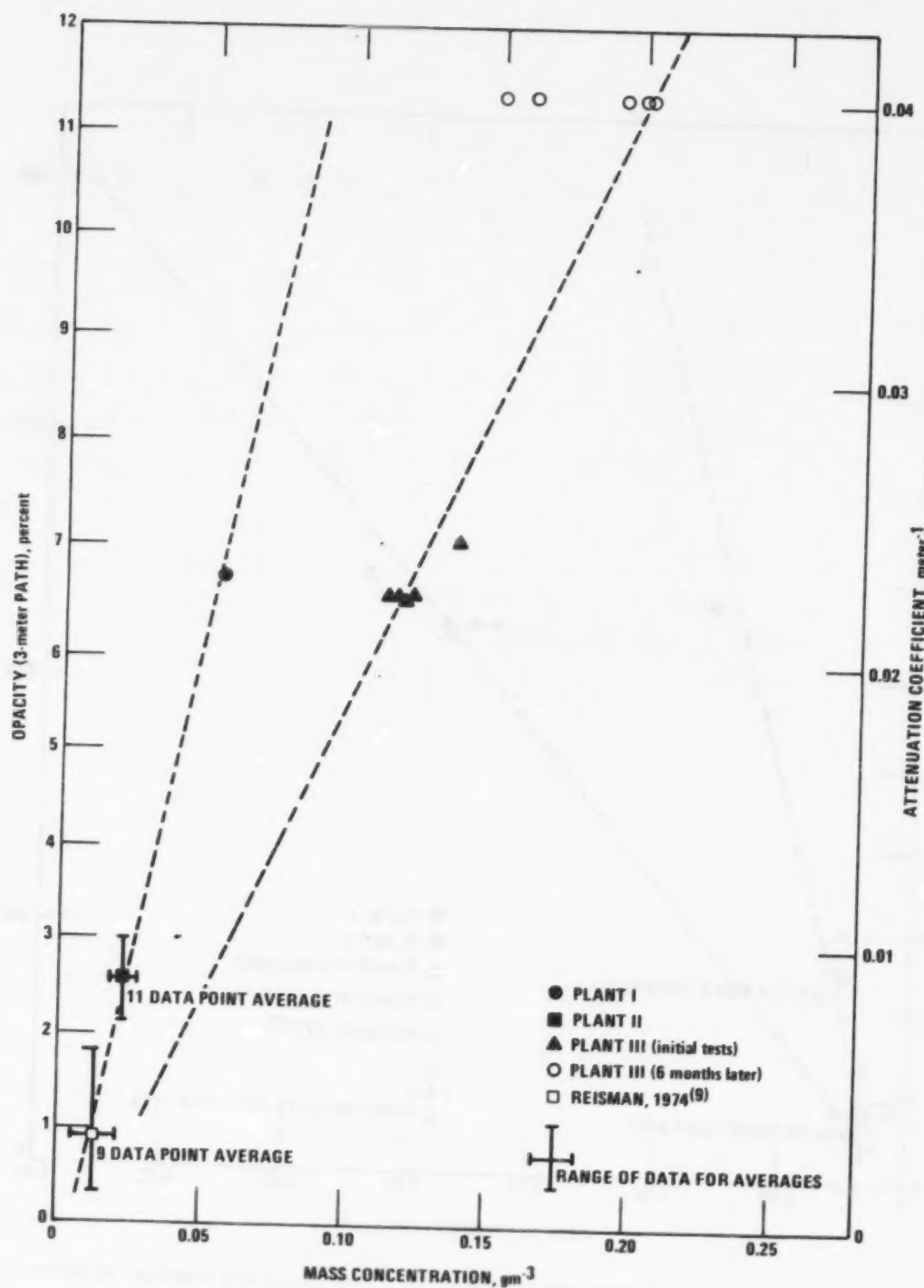


Figure 16. In-stack opacity of emissions from oil-fired power plants as a function of the mass concentration of the particulates at actual conditions.

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